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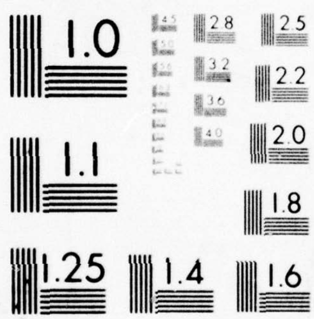

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COMPARISON OF THE PERIMETER ACQUISITION RADAR (PAR) SATELLITE TRACK CAPABILITY TO THE SPACE DEFENSE CENTER (SDC) SATELLITE CATALOGUE - UNKNOWN SATELLITE TRACK EXPERIMENT.

VOLUME I,

15

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1. INTRODUCTION

This experiment was performed by SAI under direction of BMDSC-W at the request of ADCOM. The purpose of the experiment is to determine the PAR's capability to detect and track objects that are not in the Space Defense Center (SDC) satellite catalogue, to determine the PAR's capability to reduce the potential for space tragedy for NASA's manned missions by supplementing the catalogue, and to determine some of the characteristics of the objects seen by the PAR that are not in the catalogue.

The report is divided into two volumes. In Volume I is an overview of the analysis methods, and the bulk of the results, and recommendations and conclusions. In Volume ~~I~~ 2 are the details of the analysis methods, and a set of plots showing the Radar Cross Section (RCS) distributions for PAR tracks for both those that correlated with the catalogue and those that did not for various altitude bands.

2. DATA COLLECTION PREPARATION AND DESCRIPTION

2.1 PREPARATION AND DESCRIPTION

After coordination with BMDSC and ADCOM, SAI designed the experiment, identified 22 CLC software changes, coded the changes, and tested them under SAI's Large Memory Dual Partition SAFEGUARD Tactical Simulator (STACS), an instruction level simulator of the CLC. After successful testing in Huntsville, the Configuration Management procedures were performed (References 1-4) and testing began at the PAR Site. The Technical Verification Test (Reference 5) was performed and data collected 31 July and 1 August 1976.

All objects detected in the PAR's search volume were placed in a minimum of 1/2 Hz track. The [illegible]imum search altitude was set to 100 km and the minimum search and track ranges were reduced to the minimim allowed search range. In addition, track replies were processed regardless of their sizes.

Data was collected from 06:39 CDT 31 July until 04:04 CDT 1 August 1976. The data reduced and analyzed was from 08:39 until 20:31 or for 11 hours and 52 minutes. During that time there was only one reload of the system at 15:59 resulting in a down time of 2 minutes and 6 seconds. There was essentially no aurora during the time period of the data analyzed. A total of 8445 tracks were compared to the catalogue. Multiple tracks of the same objects on the same pass were eliminated.

2.2 PAR SENSOR CHARACTERISTICS

Some PAR characteristics that influence its capabilities in the support of Space Track are briefly discussed below.

The method of surveillance is unique as compared to the SPADATS sensors. PAR has a large continuous search volume that is scanned at a high rate. This allows the PAR to have several chances at detecting any orbiting object passing through its detection volume. This allows illumination of the object

several times at various aspect angles and thus makes the probability of not detecting an object small even for low RCS objects.

The PAR also has the capability of simultaneously tracking a large number of objects. Each can be tracked with high accuracy. With biases removed SAI has shown the PAR consistently tracks Naval Astronomics Group calibration satellites with greater than 1 km accuracy (Reference 7). ADCOM analysis (Reference 6) also confirms this.

The PAR is fully automatic for detecting and tracking satellites. No manual actions are required and all objects detected are put into track.

The PAR also has the capability to search and track low altitude objects at short range due to its detection pulses being transmitted over a large range of election and azimuth angles.

3. OVERVIEW OF ANALYSIS METHODS

The purpose of this analysis was to determine the magnitude of the observed uncatalogued space satellite population. Items that would be required to accomplish this task would be: first, a catalogue of the orbital elements of the satellites now known to be in space; second, a tool for predicting the location of these satellites; and third, a tool for correlating the predicted satellite population with the actual satellite population, as tracked at the PAR Site. Section 3.1 describes the prediction method used and Section 3.2 describes the correlation method used in this experiment. More detailed descriptions of the catalogue usage and the correlation scheme may be found in Volume II of this report.

3.1 CATALOGUE USAGE

In order to perform a correlation between satellites currently maintained in the SDC catalogue and the satellites tracked by the PAR during the experiment, it was necessary to generate a data base of satellites predicted to be in the PAR's search volume during this 12 hour period. The analysis tools included in collecting the prediction data were the Satellite Catalogue Editor Program and the Satellite Report Writer Program.

Two updates of the Space Defense Center (SDC) satellite catalogue were received prior to the date of data collection, yielding a total of 3913 satellites having an epoch date greater than 76/170. The dates of the experiment were 76/213 and 76/214. The relative age of the elements in the catalogue are shown in Figure 3-1. Also note that the newest elements used for the experiment were one and a half days old.

The SDC later provided radar cross section updates for the satellite catalogue and these were also added to the catalogue for use in final analysis procedures.

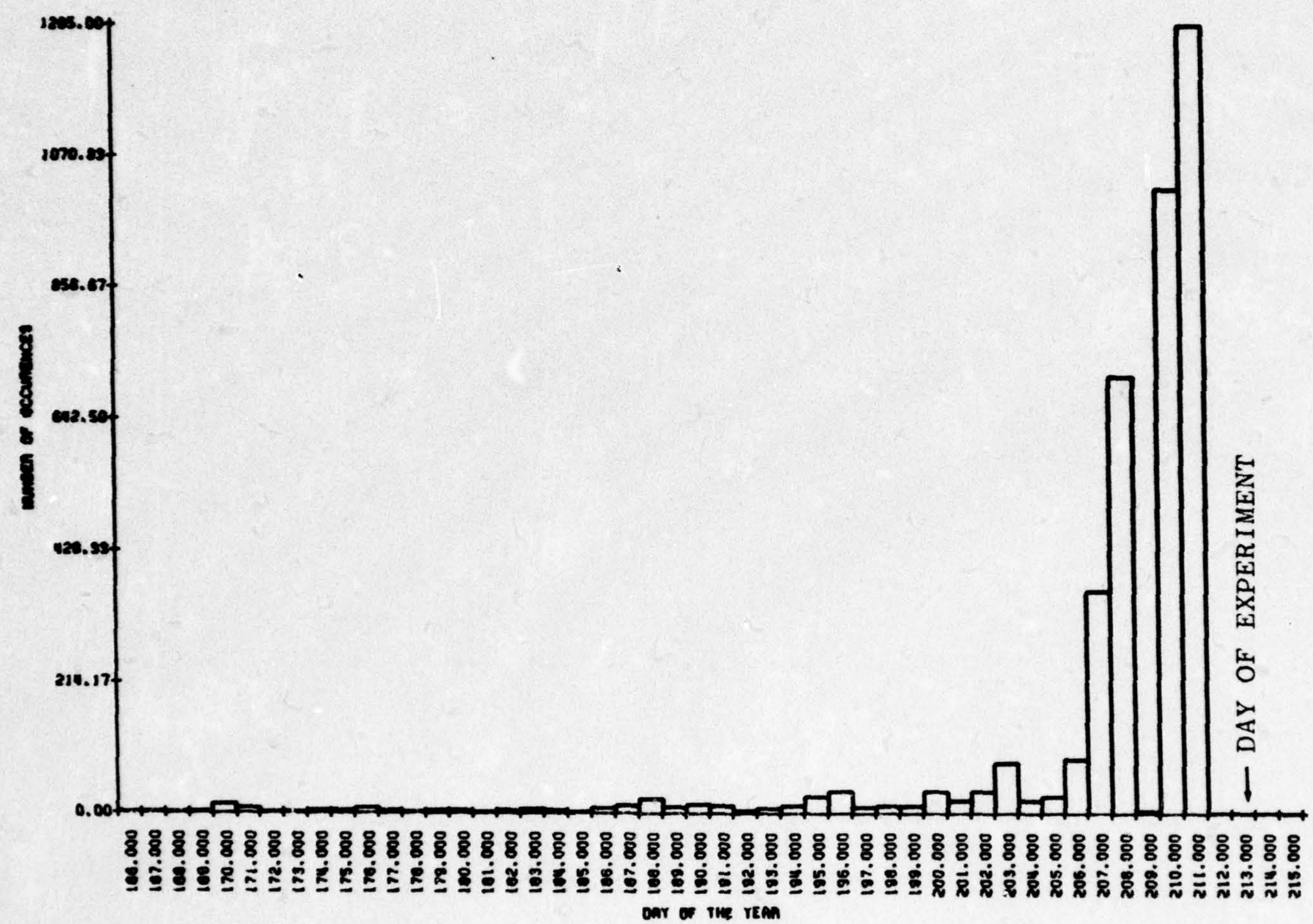

Figure 3-1. Age of Catalogue Distribution (Total Number Plotted = 3913)

The items contained within each satellite record on the catalogue are satellite identification number, epoch date, mean cross-section, mean anomaly, node of right ascension, argument of perigee, eccentricity of orbit, angle of inclination, mean motion, first and second derivatives of mean motion, drag coefficients, and semi-major axis.

The Satellite Report Writer Program accepts the orbital elements provided by the SDC's two card element set and performs simplified general perturbations in order to predict satellite positions at given times. The program was modified to handle the viewing volume peculiar to this experiment.

Once the satellite catalogue had been updated, the Satellite Report Writer Program was executed to produce the prediction of satellites expected to be in view during the 12 hour period of interest. The predictions were generated for 5 minutes before and after the experiment collection period. The Satellite Report Writer Program first read each entry in the satellite catalogue, then checked to see if the satellite entered PAR coverage, and computed entry and exit time for the satellite. An output record containing the state vector at exit time, enter and exit coverage time, altitude at exit time, satellite ID, and average RCS was then written to an appropriate file to later be processed by the satellite correlation program SATCOR.

3.2 OVERVIEW OF CORRELATION SCHEME

The correlation method consists of examining a single PAR track, and comparing its position and velocity with those satellite catalogue entries which are possible matches. If a catalogue entry is found which falls within certain bounds, a correlation is declared between the PAR track and the catalogue entry. In the event that no catalogue entry is found to match this PW track, the PAR track is declared "NEW".

The precise method used to accomplish this matching will be given in Volume II; we confine ourselves herein to the definitions of our correlation parameters together with some terms which will be used throughout both volumes of this document.

1. CORRELATION: A correlation will be declared between a PAR track and a satellite catalogue entry if the following conditions are met:

   a. The report writer has determined the satellite will exit PAR coverage within Δt (500.0 sec) of the actual PAR track vector time;

   b. The correlation program has determined that at exit the SDC and the PAR inclination differ by at most Δi ($\cos^{-1}$ .9996 ≃ 1.62 degrees); and

   c. When the catalogue vector was "flown" (either ahead or back) to the time of the PAR vector it was found that:

      (1) The magnitude of the difference of their position vectors was less than ΔP (60 nmi); and

      (2) The magnitude of the difference of their velocity vectors was less than ΔV (where ΔV varied between .5 kft/sec for the best quality PAR track and 12.5 kft/sec for the worst quality acceptable PAR Track).

2. NEW: A PAR track was declared new if it did not correlate with any catalogue entries.

3. MISS: A catalogue entry was declared missed if no PAR tracks correlated with it.

4. MULTIPLE CORRELATION: Occurs when two or more PAR tracks correlate with a single catalogue entry.

In implementing this correlation technique, significant effort was expended to reduce the number of non-correlating PAR tracks as much as possible. The first thirty-five minute period of data was analyzed in great detail. All "NEWS", "MISSES",

and "CORRELATIONS" were individually evaluated. The correlation bounds were enlarged as large as possible without creating a significant increase in the number of multiple PAR vectors correlating with the same SDC vector. Enlarging the out-of-plane prefilter and the distance correlation bound yielded a few new multiple correlations and very few additional correlations. The additional correlations had poor matches in distance, velocity, and inclination of orbit plane. This implied that the object tracked should not have been correlated. The correlation bounds used are considerably larger than those used for association checks by the SDC.

"CORRELATION" as used here corresponds to the term "ASSOCIATION", used at the SDC.

3.3 CAUSES OF NON-CORRELATIONS

Listed below are some of the reasons that a PAR track may not correlate with the catalogue.

Of course, the object tracked may not have an entry in the catalogue; thereby being uncatalogued.

An object may have been tracked by the SPADATS system but does not have sufficient coverage to be regularly tracked or the fence detection scheme used does not have a high probability of redetecting the object; and therefore, an entry can not be sufficiently maintained in the catalogue. The entry in the catalogue may be old and the satellite therefore "lost".

The low altitude objects do not have stable orbits due to atmospheric drag. Catalogue elements that are very old have large errors, and these elements are difficult to maintain. In addition, the objects are difficult to detect at low altitude since the SPADATS detection fences are at low elevations and therefore long range.

The high PAR system detection probability previously described (Section 2.2) allows it to detect objects that may not be generally detected by the SPADATS system.

A poor PAR track may also cause a non-correlation. However, the data presented in Sections 4.2.6, 4.2.5 and 4.2.2 indicate that this is unlikely for nearly all non-correlating tracks.

4. RESULTS

4.1 SUMMARY OF RESULTS

The most conclusive statement that may be made regarding this experiment is that there are indeed objects orbiting the earth that can be seen by the PAR and which do not correlate with specific satellite catalogue entries. Further, this set of objects represents 17.7% of the total population of objects tracked by the PAR.

These general statements are made by assuming that this 12 hour experiment is representative, an assumption which is supported by the fact that the rate was relatively constant throughout the experiment. The analysis to date has been concentrated on the achievement of confidence in this rate through examination of correlation techniques and the tuning of various correlation parameters.

Some work has, however, been directed towards a qualitative evaluation of both the correlations and new tracks. The highlights are as follows:

1. The "NEW" tracks tended to be of lower average radar cross section than the correlations and the entries in the catalogue.
2. Roughly 90% of the PAR tracks less than 400 km and 62% of those below 500 km in altitude failed to correlate.
3. There appears to be at least one group of about 190 "NEW" PAR tracks which share a common inclination and altitude band and may be the result of a known breakup.

4.2 CHARACTERISTICS OF DATA

It is desirable to know the characteristics of the results just presented. Various parameters that can be used to describe the characteristics of the PAR tracks will be discussed in this section.

The intent of the rest of this section is to detect trends in the data, to present information necessary for confidence in the results and to give the reader some insight into the quality of the data. A detailed analysis of the entire experiment and data is not attempted here.

Section 4.3 contains a summary of the characteristics found in the following sections.

4.2.1 Correlations as a Function of Time

In Figure 4-1, the time cumulative number of PAR tracks that correlated with the catalogue and the time cumulative number of correlated and non-correlated (new) tracks are plotted against time. The plot demonstrates the fact that during the approximately 12 hours of data collected there was no significant deviation of the ratio of new tracks to total tracks. This indicates that the 17.7% of PAR tracks not correlating with the catalogue is a relatively time independent value. The flat portion of the curves at 213.87 days is the time period of the reload of the software during data collection at the PAR.

4.2.2 Correlation Distance Distributions

In order to establish confidence in the correlation scheme and to establish a measure of the accuracy of the experiment, various correlation parameters are computed and plotted.

The correlation distance is defined as the distance between the PAR state vector and the state vector generated from the catalogue at the PAR vector time. A value less than 60 nmi was one requirement for correlation. The SDC objective is to maintain a 12 km accuracy on the field elements in the catalogue. Of all the PAR tracks that correlated with the catalogue,

69% correlated with distance error less than 6.5 nmi (12 km)
80% correlated with distance error less than 10 nmi (18.5 km)
95% correlated with distance error less than 25 nmi (46.3 km)
99% correlated with distance error less than 50 nmi (92.7 km)

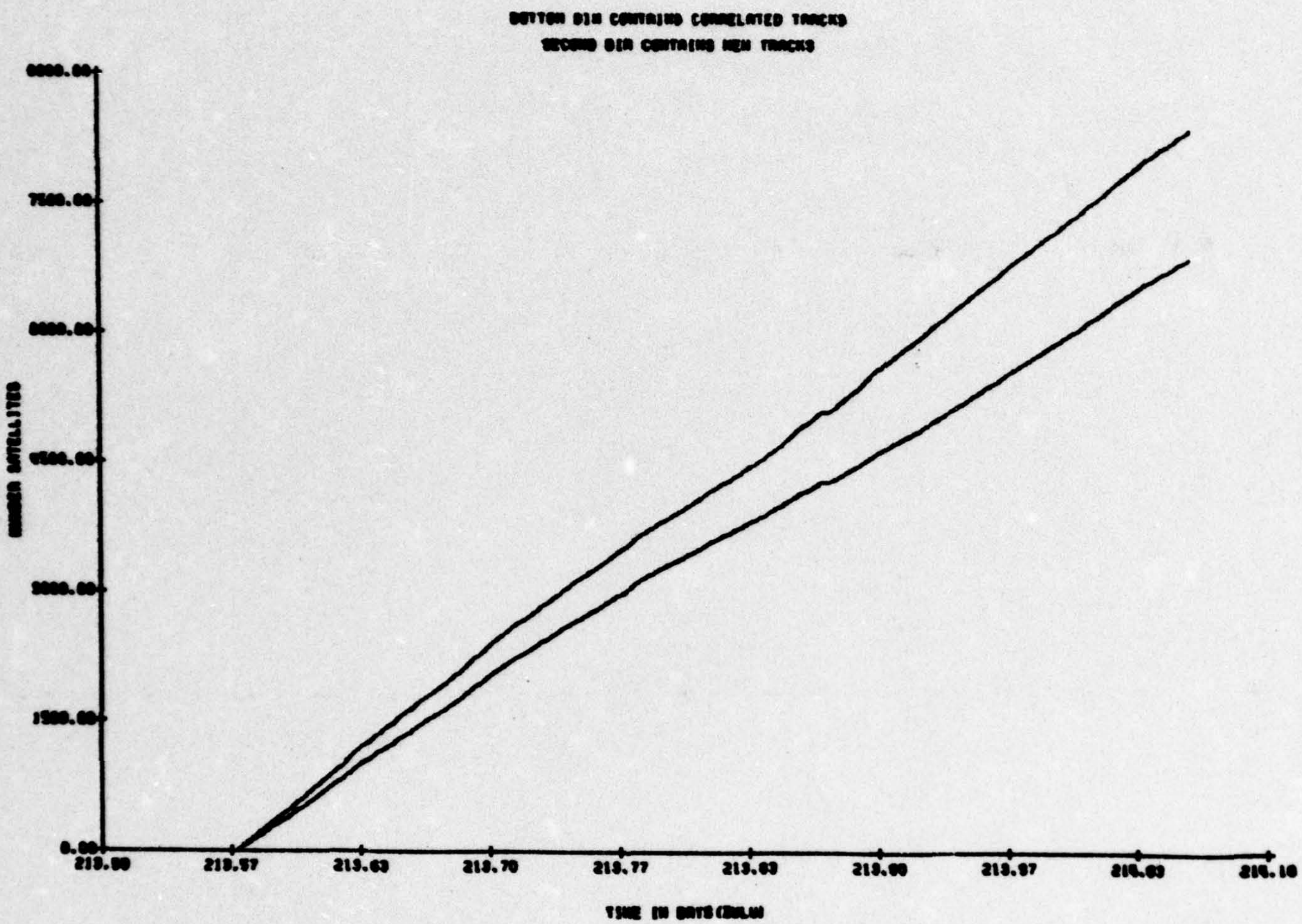

Figure 4-1. New and Correlated Tracks as a Function of Time

Figure 4-2 is a scatter plot showing the distribution of the correlation distances as a function of altitude. No trend is discernable, indicating that in the altitude regions applicable for this experiment, the accuracies of the PAR tracks relative to the catalogue do not appear to be altitude dependent.

Since SDC catalogue elements were used with epoch dates as old as 43 days, the distribution of correlation distance as a function of age of the corresponding catalogue entry was plotted in Figure 4-3. The most obvious characteristic noted was that only 4 correlations with elements older than 13 days were made. Approximately 230 of the 3913 entries in the catalogue used were older than 10 days. These 4, however, had very good correlation distances indicating good prediction accuracy for our catalogue predictor.

Since some fairly short PAR tracks were included in the correlation analysis, the correlation distance as a function of the number of PAR track points was computed to establish confidence in these shorter tracks. In Figure 4-4, is plotted the correlation distance as a function of number of track points. As all tracks were conducted at a minimum of 1/2 Hz, the maximum possible time in track can be approximated by the number of track points multiplied by two.

Since the PAR can track at better than 1 km accuracy after bias corrections, even considering the fact that the catalogue elements used for this experiment were 1½ days or more old, it appears that the PAR can contribute to a more accurate catalogue by updating already catalogued elements. For this experiment, known biases in the PAR were removed from the vectors before correlation was attempted. A feasible use of the PAR in an automatic SPADATS role would be for it to report vectors to the SDC for correlation distances greater than 12 km as well as for tasked or non-catalogued objects. These characteristics and others to be discussed later tend to confirm the conclusions of the ADCOM experiment of Spring 1975. That experiment

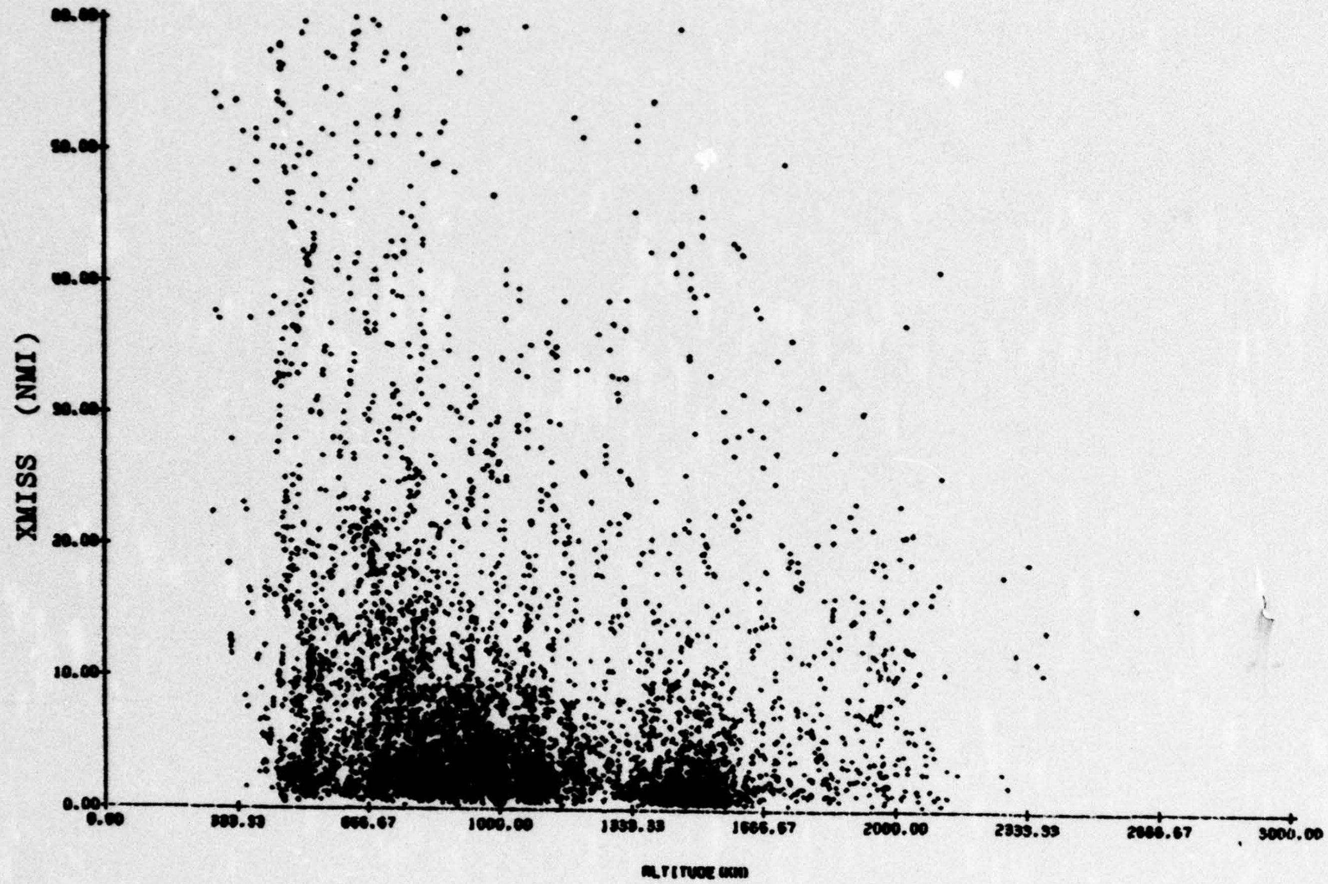

Figure 4-2. Correlation Distance as a Function of Altitude (Correlation Tracks Only)

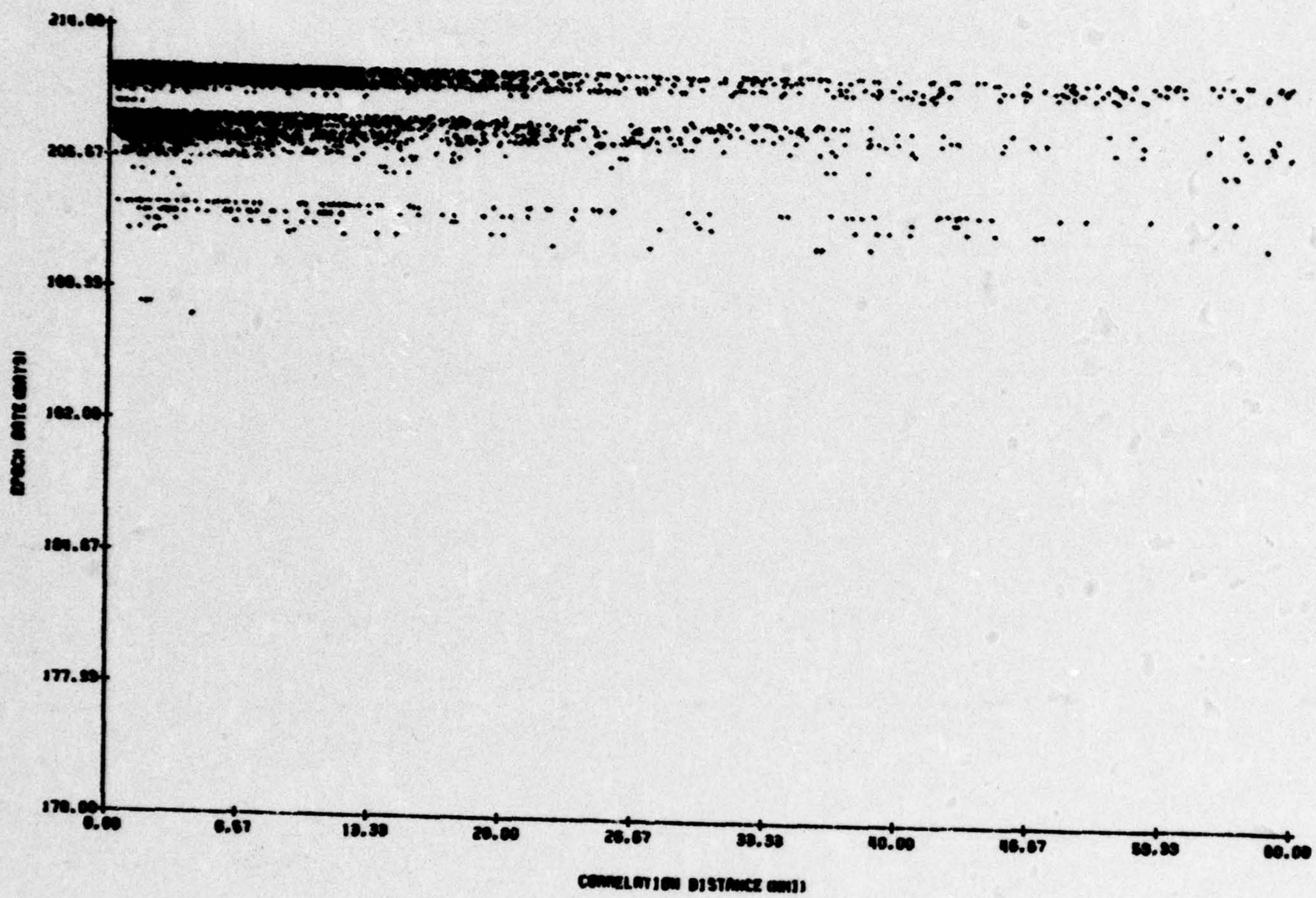

Figure 4-3. Correlation Distance vs Catalogue Element Epoch Date

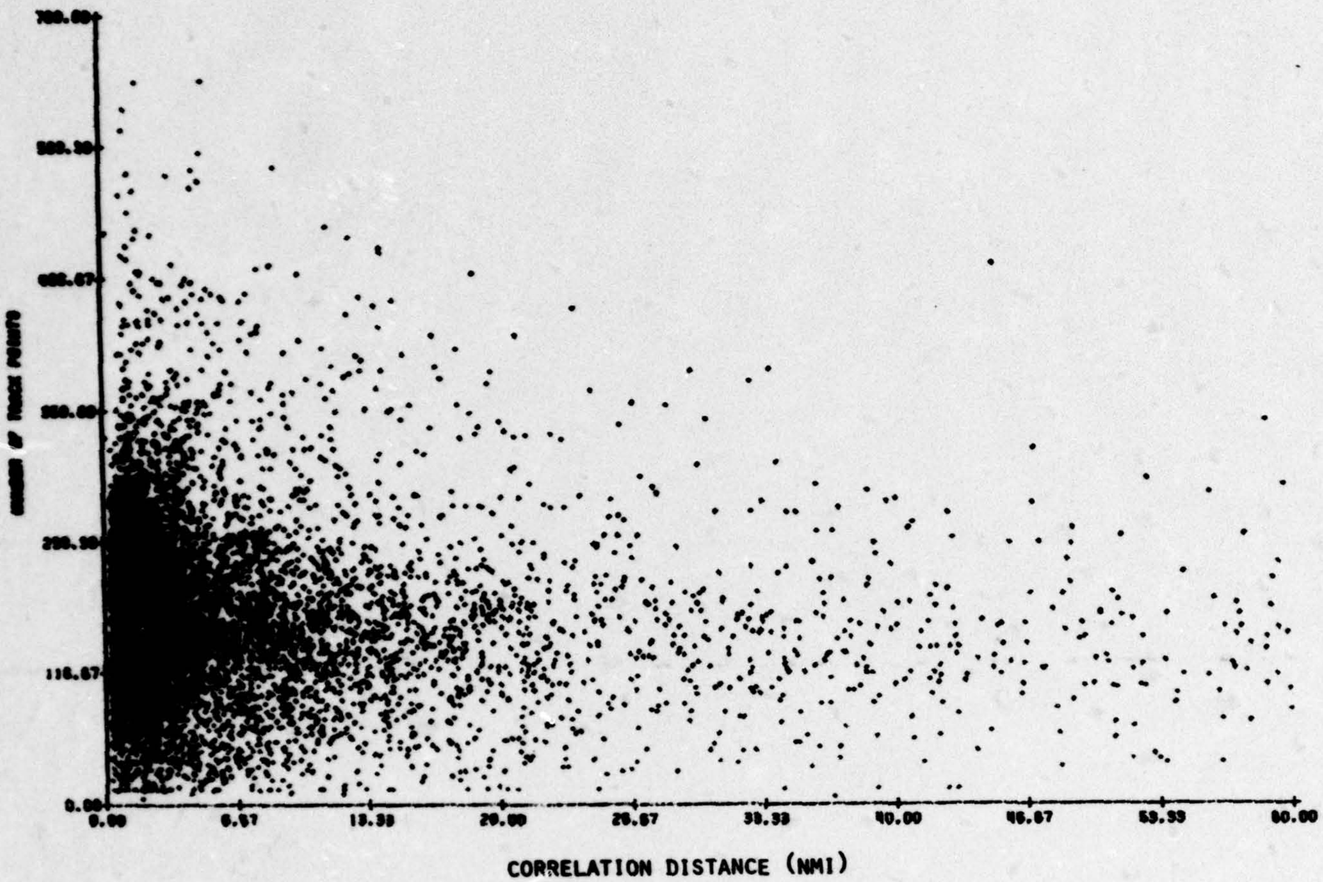

Figure 4-4. Number of Track Points as a Function of XMISS (Correlation Tracks Only)

among other things, concluded that the PAR could improve the accuracy of the catalogue (Reference 6).

4.2.3 Characteristics of Non-Correlations

Of the 1494 tracks that did not correlate, only 2% were within 60 nmi of an SDC vector integrated to the PAR vector time. This 2% did not pass the velocity correlation bound. Of the 24 tracks failing the velocity check, other PAR tracks correlated with 14 of the corresponding SDC vectors for those passes of the objects. This indicates a very probably correct non-correlation call by the velocity check. An additional 2 of the 24 were 80 thousand series entries (candidates for the catalogue with possible poor vectors) and one of the remaining SDC entries had an epoch date 7 days old. Three of the remaining velocity correlation failures had more than 50 PAR track points indicating relatively good state vectors. Thus, that leaves only 5 tracks that were called non-correlated due to velocity that possibly could have correlated given better tracks.

59% of the non-correlated PAR tracks had the orbit plane within $1^{o}37'$ of an orbit plane in the SDC catalogue but had more than a 60 nmi correlation distance. The remaining 39% were not within $1^{o}37'$ of an orbit plane in the catalogue for which an SDC vector could be generated within 500 seconds of the PAR vector. Details of the correlation scheme can be found in Section 3.2 and in Volume II of this report.

4.2.4 Radar Cross Section Distributions of Tracks

In Figure 4-5 are plotted histograms of the RCS's of the PAR tracks which correlated with the catalogue and of the RCS's of the PAR tracks that did not correlate. (It should be noted that in the RCS plots the horizontal scales are changed each decade.) The correlations are plotted with the solid lines and the sum of the new tracks and the correlations are plotted as dotted lines. The new tracks are more predominant for the smaller RCS's. This trend indicates that the PAR generally

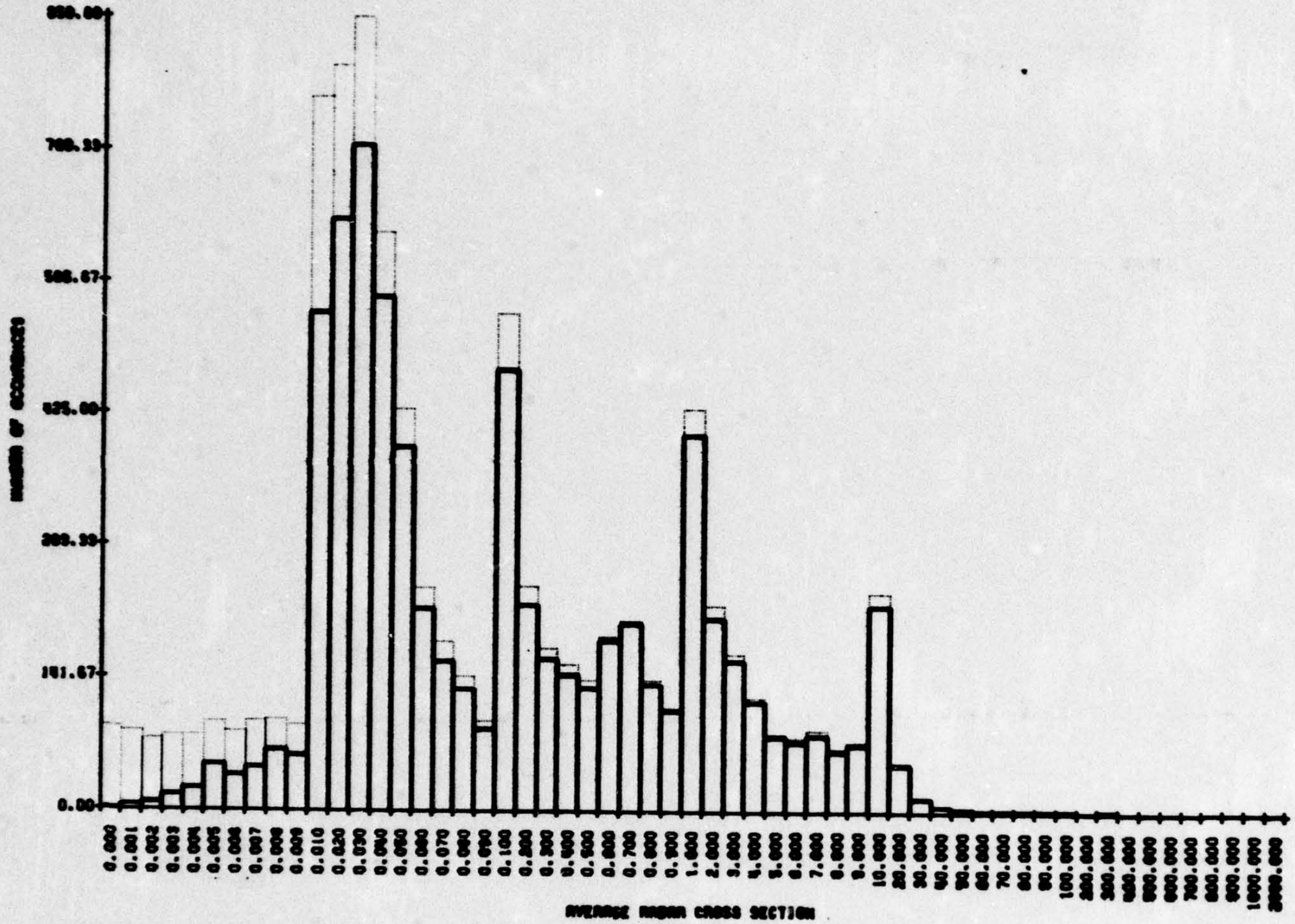

Figure 4-5. RCS Distribution of Correlated and New Tracks

has a greater sensitivity than the rest of the SPADATS system. In Figure 4-6, an RCS histogram of only the new tracks is plotted so that their distribution can be more easily observed. Figures 4-7, 4-8, and 4-9 contain RCS distributions for correlated and non-correlated tracks for altitude bands of 100-200 km, 100-300 km, and 100-400 km. Note that in these regions practically all objects observed by the PAR were not in the catalogue. Volume II of this report contains these type plots for 50 km altitude bands from 100-2000 km.

In order to determine the extent of which the PAR mapped the small cross section objects in its view, the scatter plots in Figures 4-10, 4-11, and 4-12 were generated. In Figure 4-10 is plotted the range of the track at correlation time versus the log of the RCS in square meters. From this plot, it can be observed that the smaller RCS objects were tracked at shorter ranges as is expected. From Figure 4-11a the same trend in altitude can be observed. The PAR could, however, see the smaller RCS's at higher altitudes by raising the maximum elevation of the search raster. For this experiment the maximum elevation was about 40°. Thus, with a higher elevation for the search beams, the PAR could see smaller RCS's at higher altitudes (and lower inclinations and latitudes) due to the fact that the higher altitudes would be at shorter ranges with higher elevations. Therefore, it is expected that with a higher elevation search raster there would be more data in the area of Figure 4-11a for small RCS and larger altitudes, and that the 17.7% of PAR tracks not correlating with the SDC catalogue should have been larger. With the overlay on Figure 4-11a, the distribution of all PAR tracks in RCS and altitude can be compared to the same distribution for the catalogue. Figure 4-11b contains similar data for only those tracks that did not correlate with the catalogue. From these plots, it can be seen that a large number of the objects the PAR tracked that did not correlate were also at lower altitudes. See Section 4.2.11 for details.

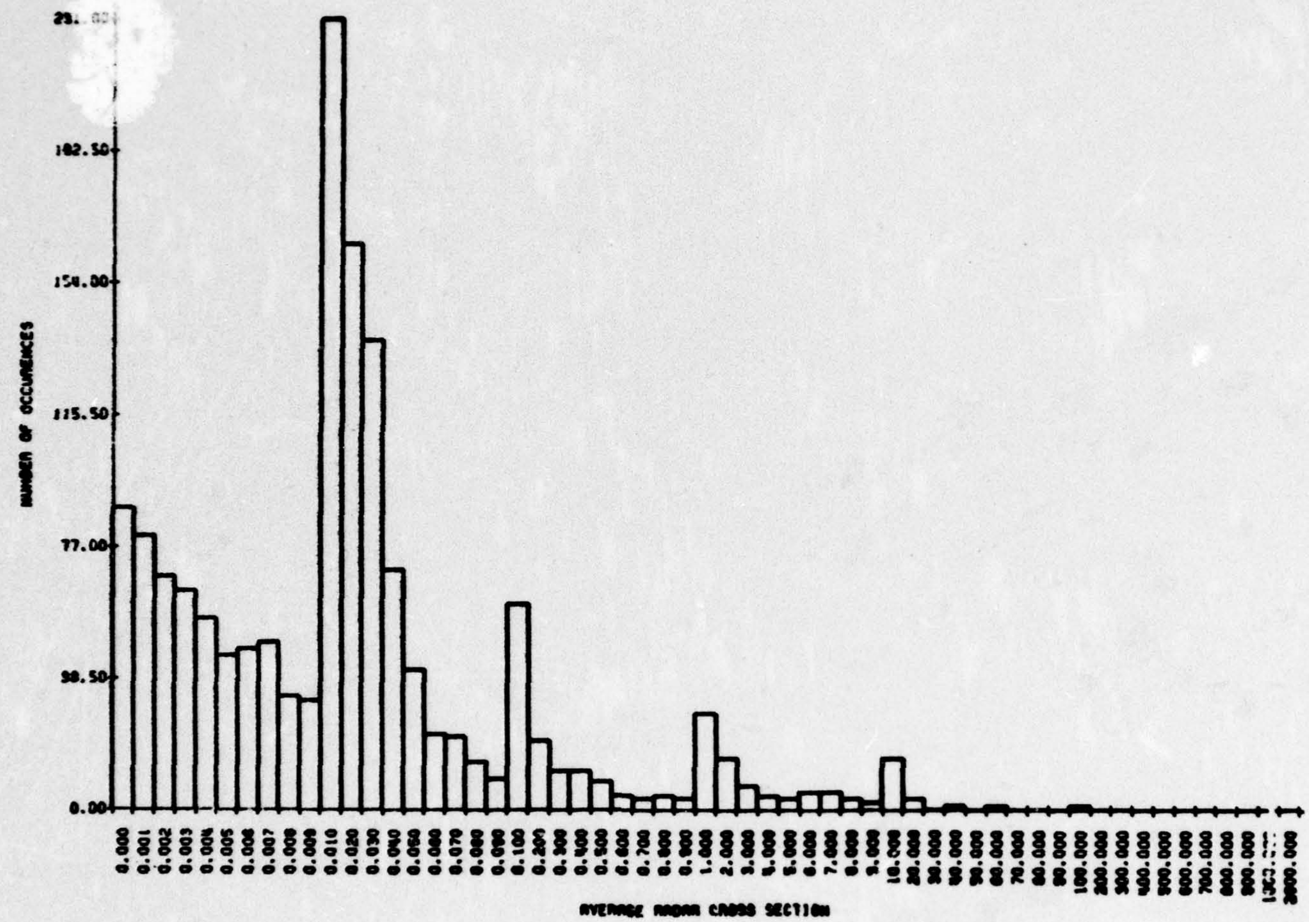

Figure 4-6. RCS Distribution of New Tracks

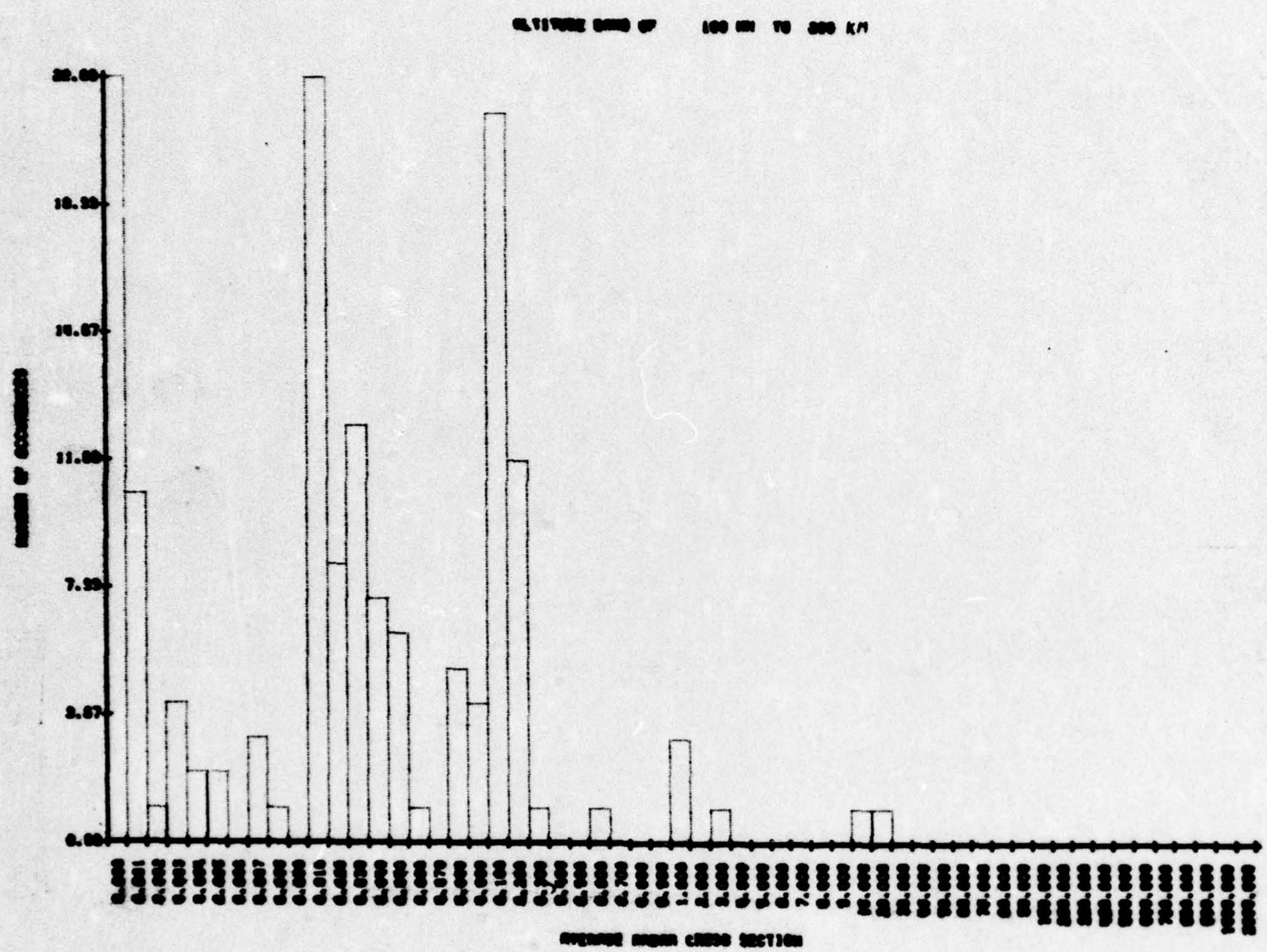

Figure 4-7. RCS Distribution of Correlated and New Tracks

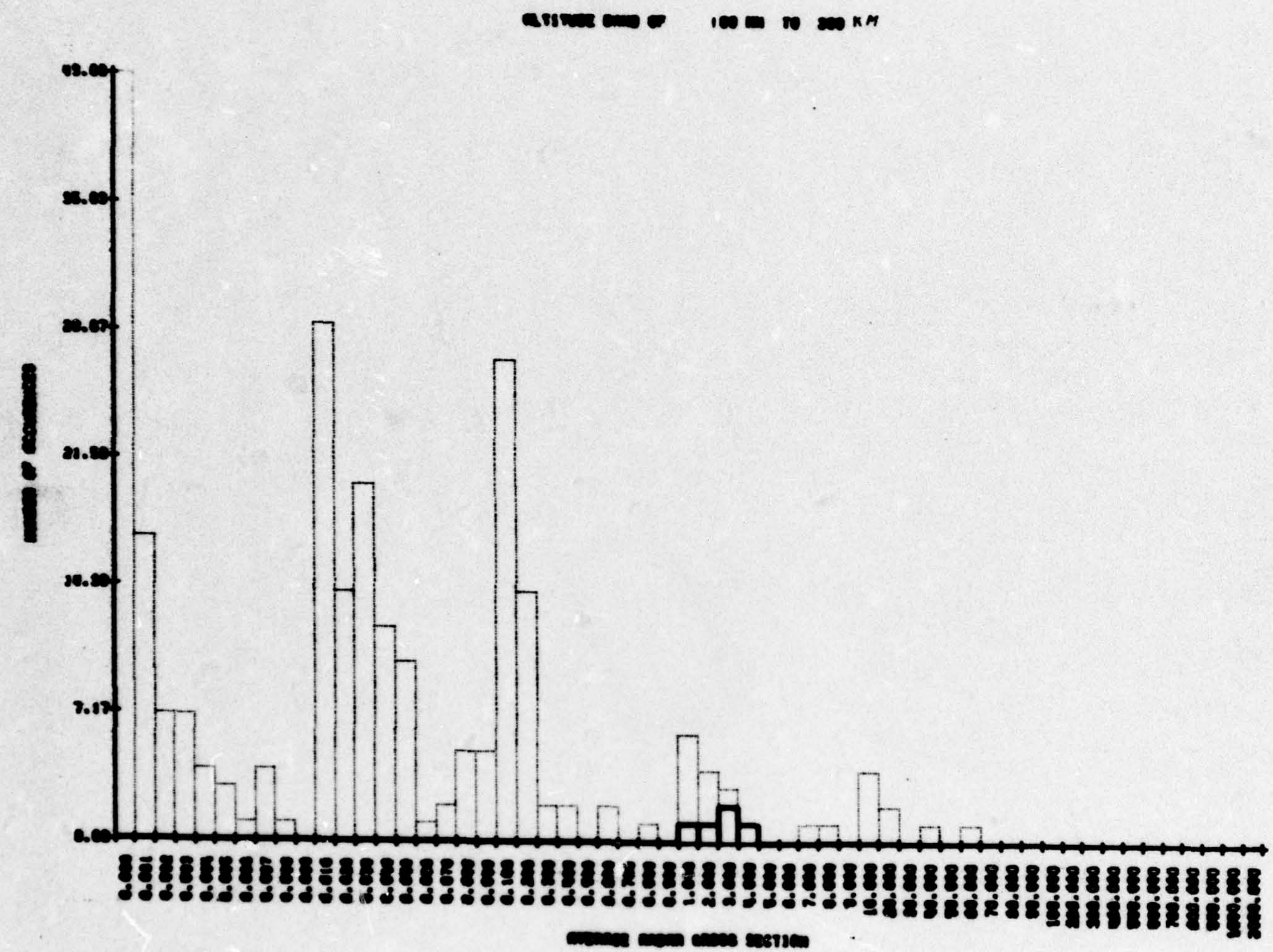

Figure 4-8. RCS Distribution of Correlated and New Tracks

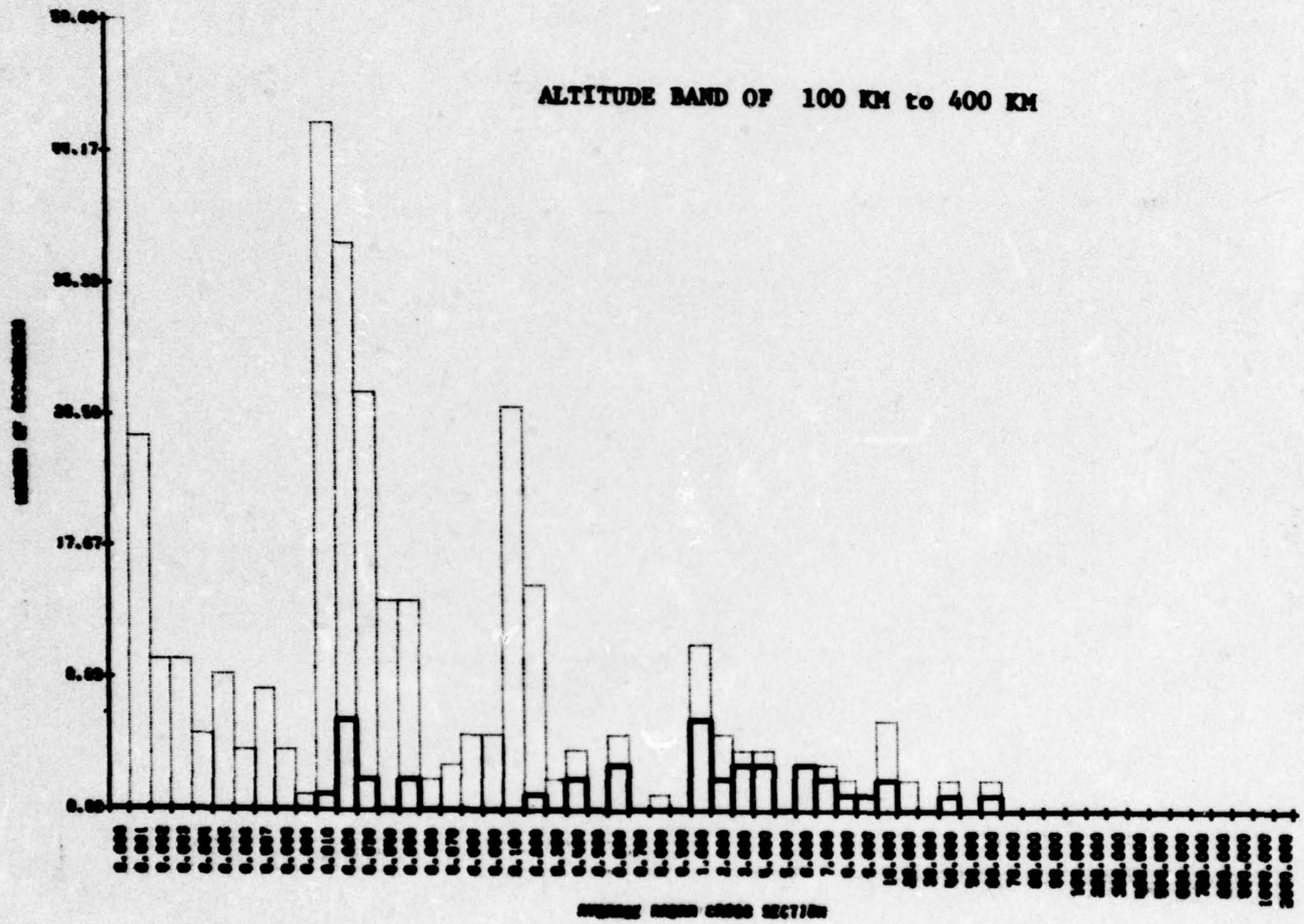

Figure 4-9. RCS Distribution of Correlated and New Tracks

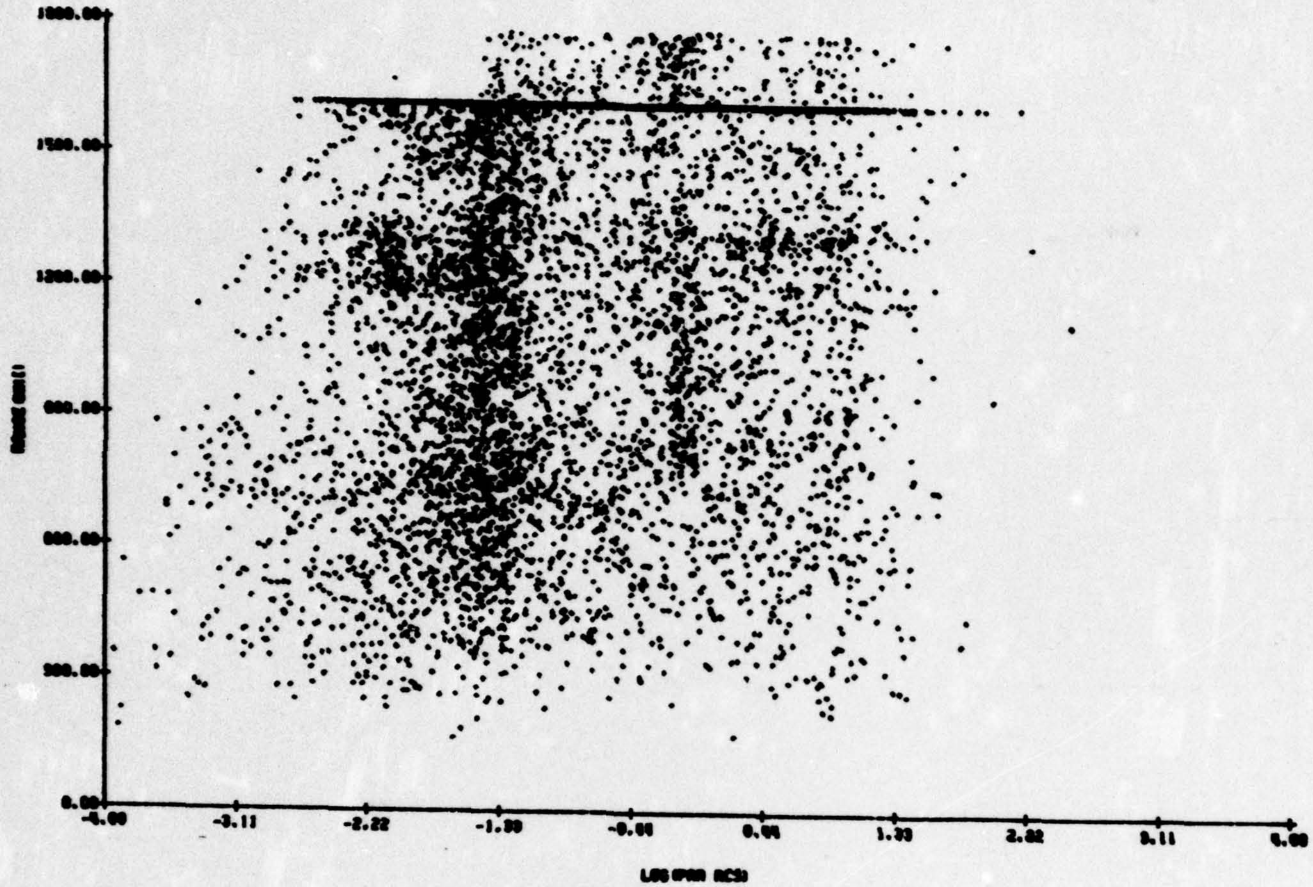

Figure 4-10. Range as a Function of RCS (New and Correlated Tracks)

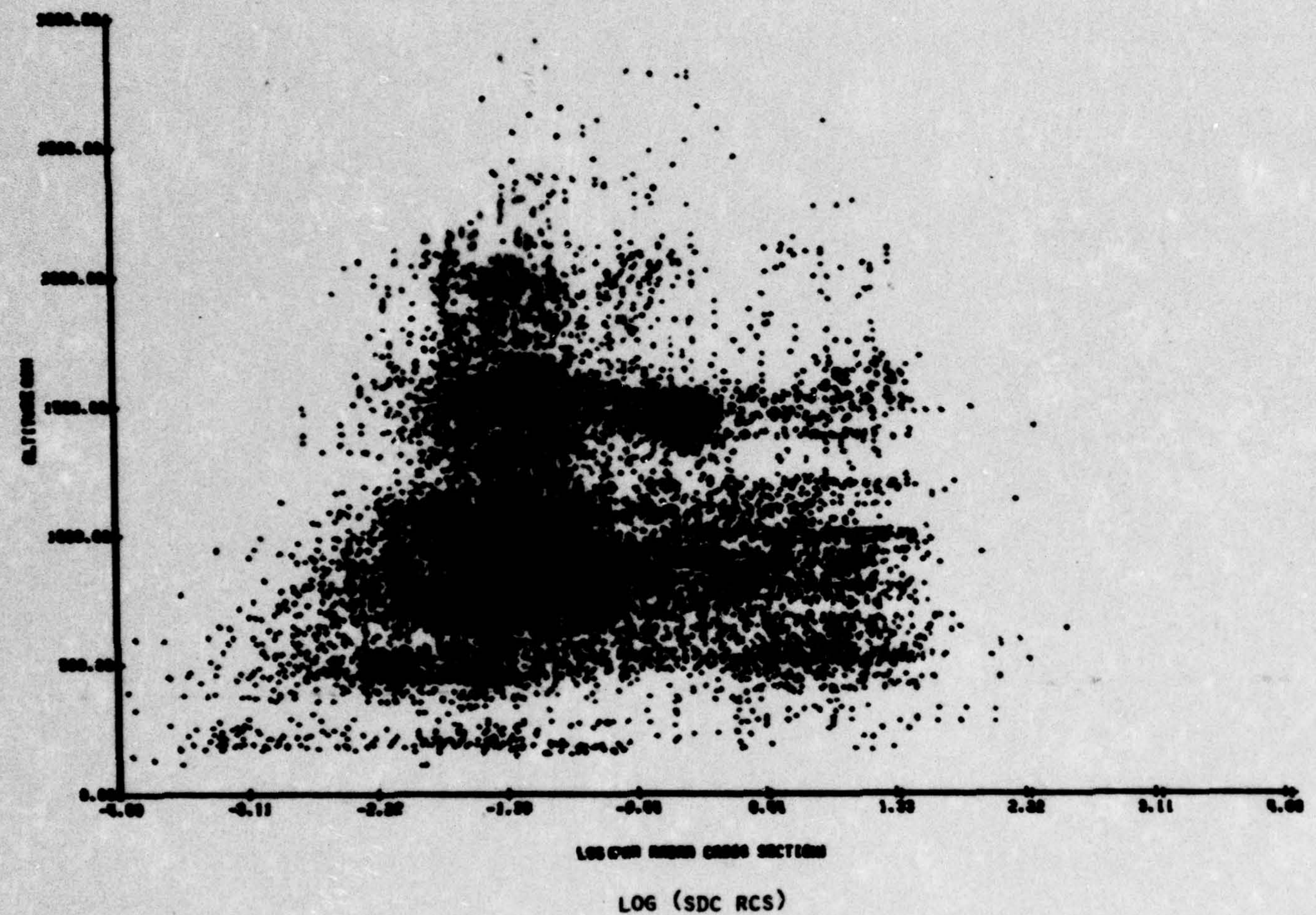

Figure 4-11a. Altitude Distribution of RCS's (New and Correlated Tracks)

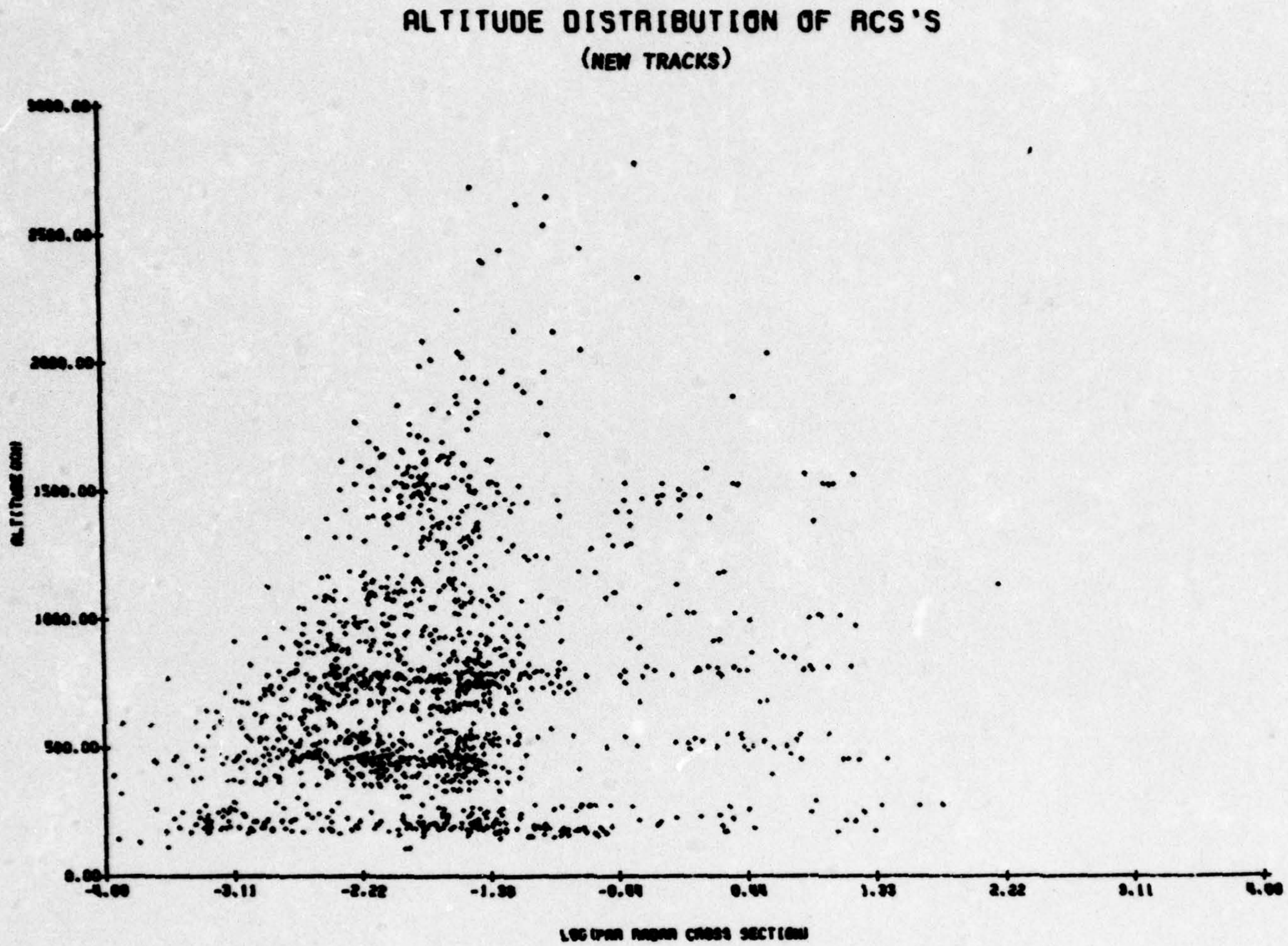

Figure 4-11b. Altitude Distribution of RCS's (New Tracks Only)

It is also of interest to determine if the objects with smaller RCS's that correlated with entries in the catalogue, may have had larger correlation distances. Correlation distance (XMISS) versus the log of the PAR measured average Radar Cross Section in square meters is plotted in Figure 4-12. The only higher density of large correlation distances occurs at the same RCS values as the most dense RCS's in the population (compare Figures 4-12 and 4-11a). No definite trend is readily observable. It, therefore, appears that the small cross section objects that did not correlate with the catalogue failed to correlate due to their absence from the catalogue rather than poor vectors (from the PAR or the catalogue).

To determine if the smaller RCS's had generally shorter track lengths the number of track points was plotted versus the log of the RCS in Figure 4-13. No such trend is apparent; in fact, some of the smaller RCS objects had a larger number of track points. (This is partly due to the dynamic pulse scheduling that can allow a higher track rate than 1/2 Hz for the poorer tracks).

4.2.5 Distribution of Track Lengths

Just as the number of track pulses expended as a function of RCS was of interest, the number of track points as a function of altitude is of interest since a large percentage of the non-correlating tracks were at low altitudes. Figure 4-14 is a plot of the data and shows that at low altitudes there tends to be shorter lengths of track. This smaller number of low altitude track points are primarily a function of the size of the low altitude viewing volume of the PAR. As previously indicated with the overlay to Figure 4-11a, the very low altitude objects generally are not in the catalogue and thus can not be said to have not correlated due to poor PAR track vectors or poor catalogue entries.

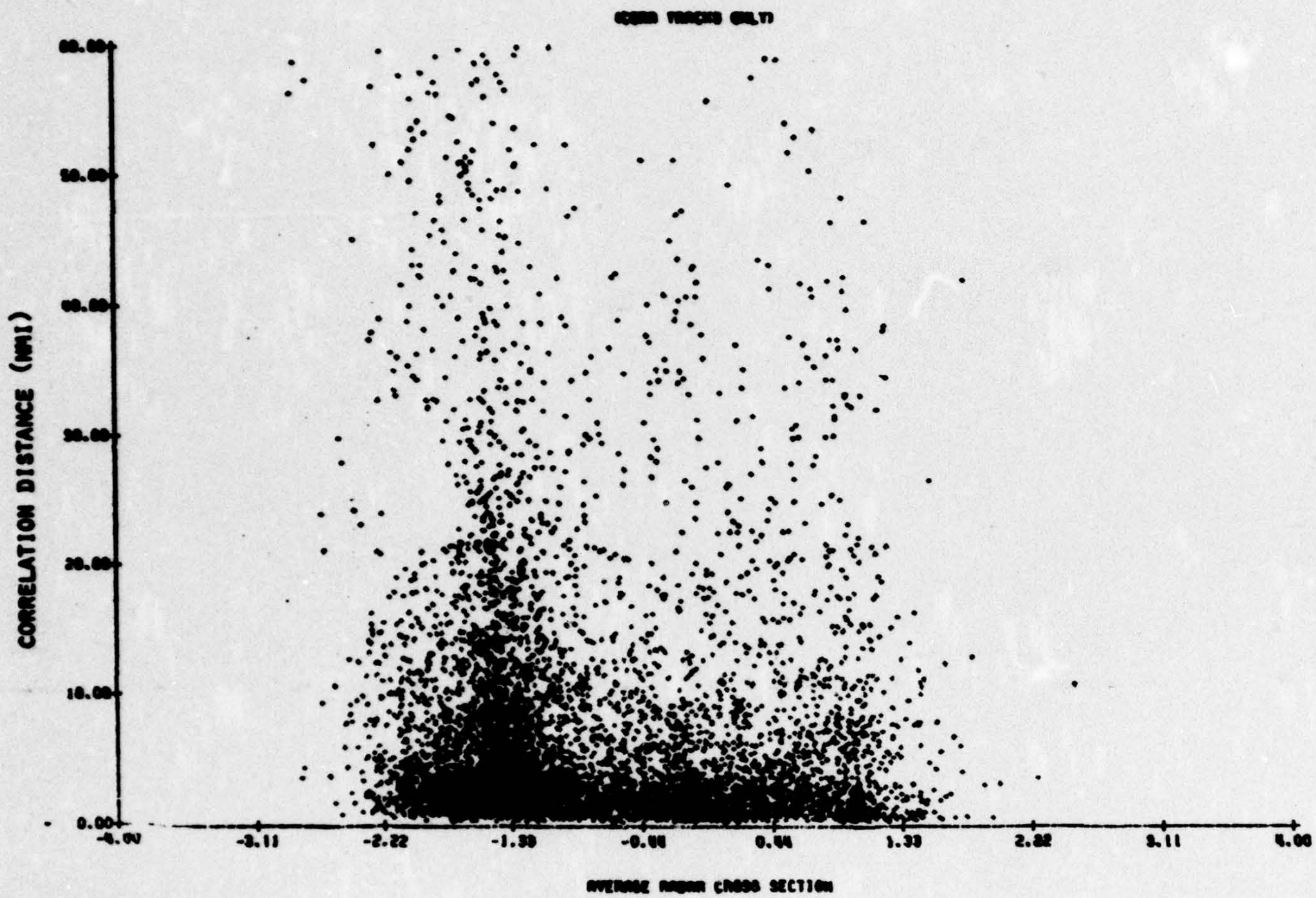

Figure 4-12. RCS As a Function of XMISS

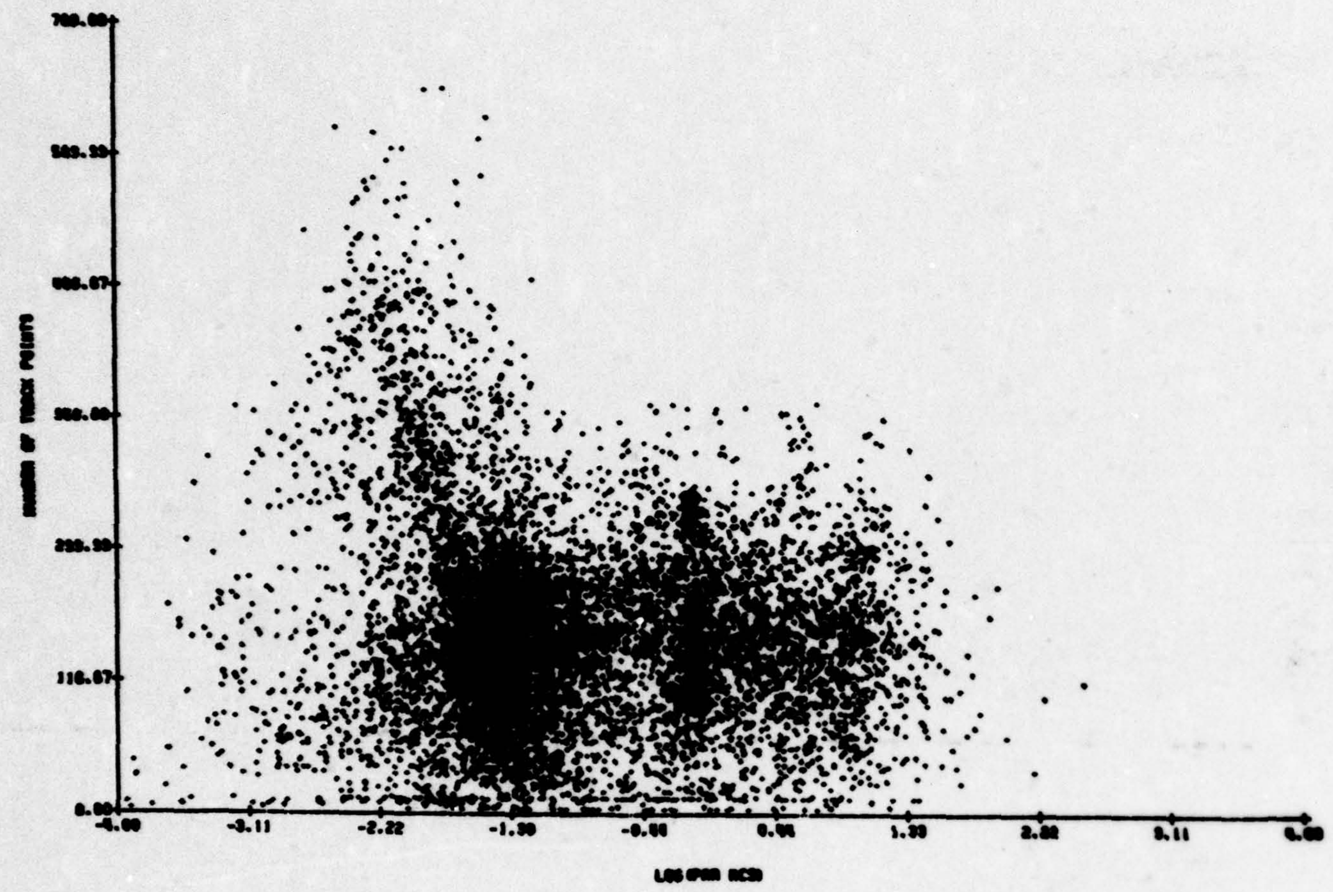

Figure 4-13. Number of Track Points as a Function of RCS (New and Correlated Tracks)

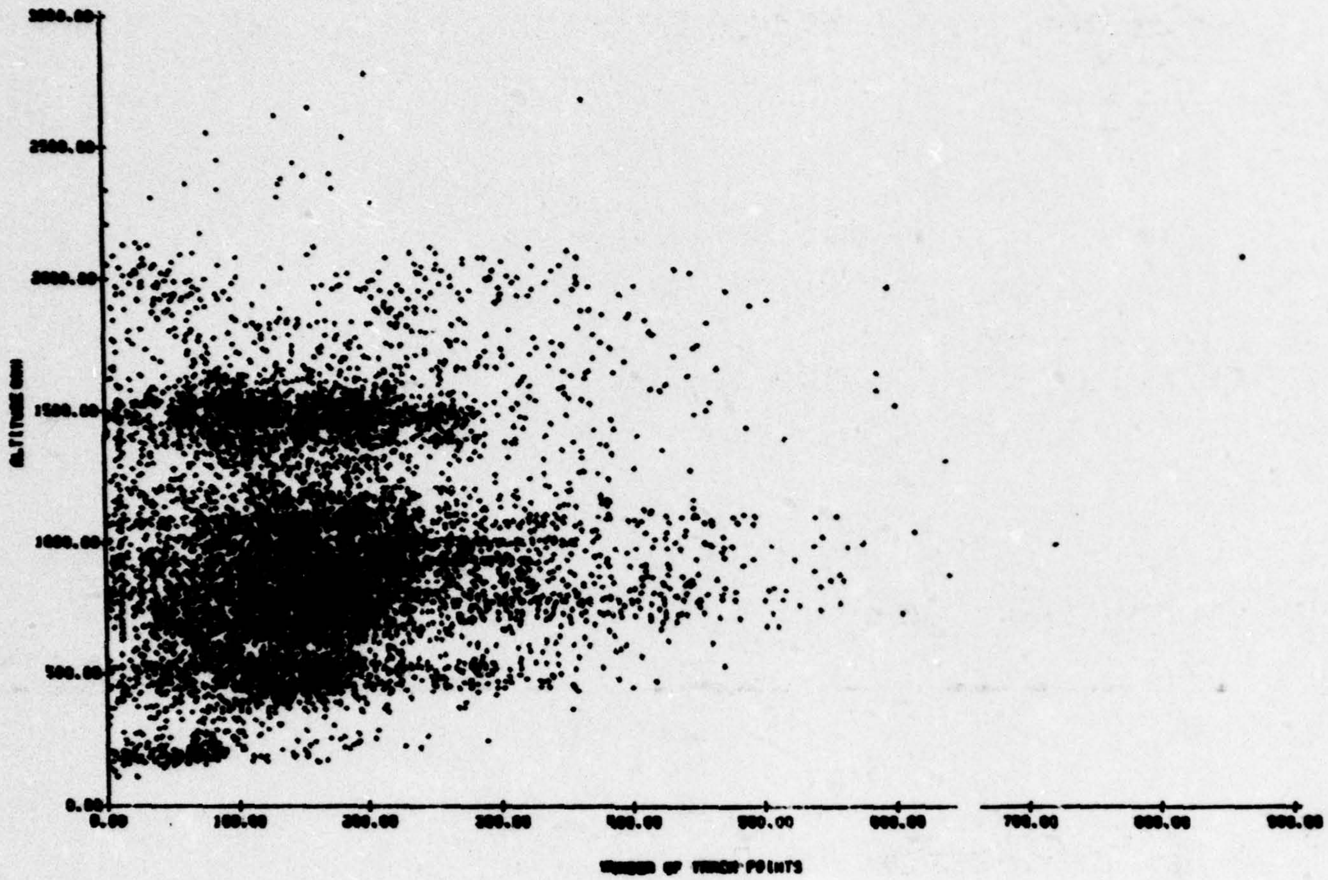

Figure 4-14. Altitude as a Function of Track Points (New and Correlated PAR Tracks)

The distribution of track lengths for both the correlated and non-correlated tracks is plotted in Figure 4-15. The non-correlated tracks are plotted incrementally above the others. There are some short tracks which did not correlate. Of the tracks in the first bin, 42 are at altitudes below 500 km and about 20 have RCS's less than .005 m^2 and about 100 less than .1 m^2. These are characteristics generally describing new tracks and account for a large part of the new tracks in the first bin. From Figure 4-4, however, it appears that track length is not a contributing parameter to non-correlations.

4.2.6 Distributions of Track Velocity Sigmas

Because the PAR generated velocity vector is used for both the orbital plane prefilter and as a direct check in the correlation scheme, the distribution of velocity track sigmas for the tracks that correlated and did not correlate were examined. Plotted in Figures 4-16a and 4-16b is a histogram that is the distribution of the velocity sigmas for each PAR track. For simplicity, the sigma plotted is the square root of the sum of the squares of the three velocity sigma components. For a PAR track to fail the out-of-orbital plane check it would have to have an out-of-orbital plane velocity component of about 600 ft/sec. From Figures 4-16a and 4-16b it can be seen that the total velocity sigma is consistently smaller than 600 ft/sec. The number of non-correlations which could have an out of plane velocity sigma component greater than 600 ft/sec is a small percentage of the total non-correlations.

4.2.7 Inclination Angle Distribution

The distribution of inclination angles observed is plotted in Figure 4-17. As previously mentioned, the range of inclination angles observable can be enlarged by raising the maximum elevation of the PAR search volume. It should be noted that the PAR's "Special Track" capability of establishing track on a specific satellite at a known position can be done at any

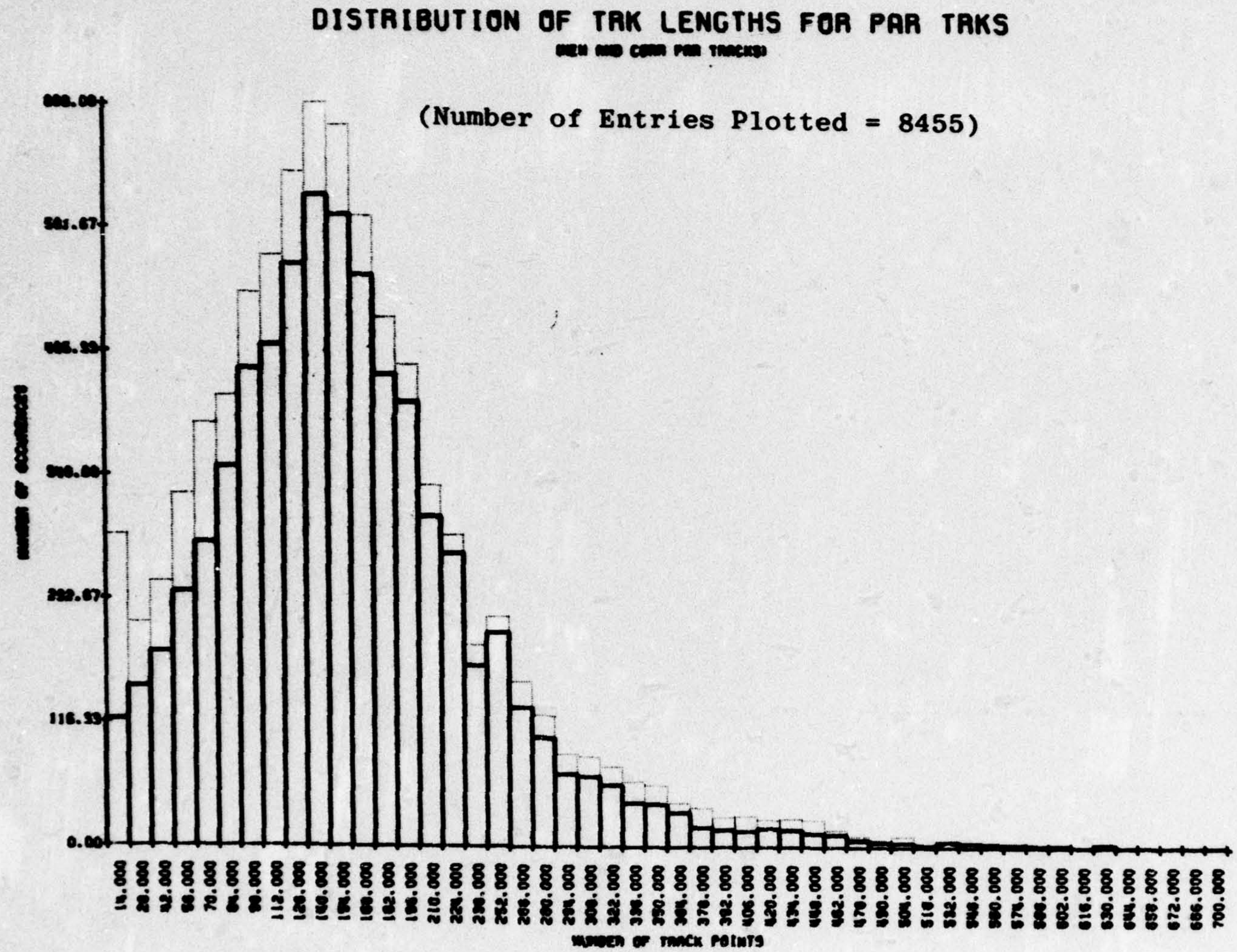

Figure 4-15. Distribution of Track Lengths for PAR Tracks
(New and Correlated PAR Tracks)

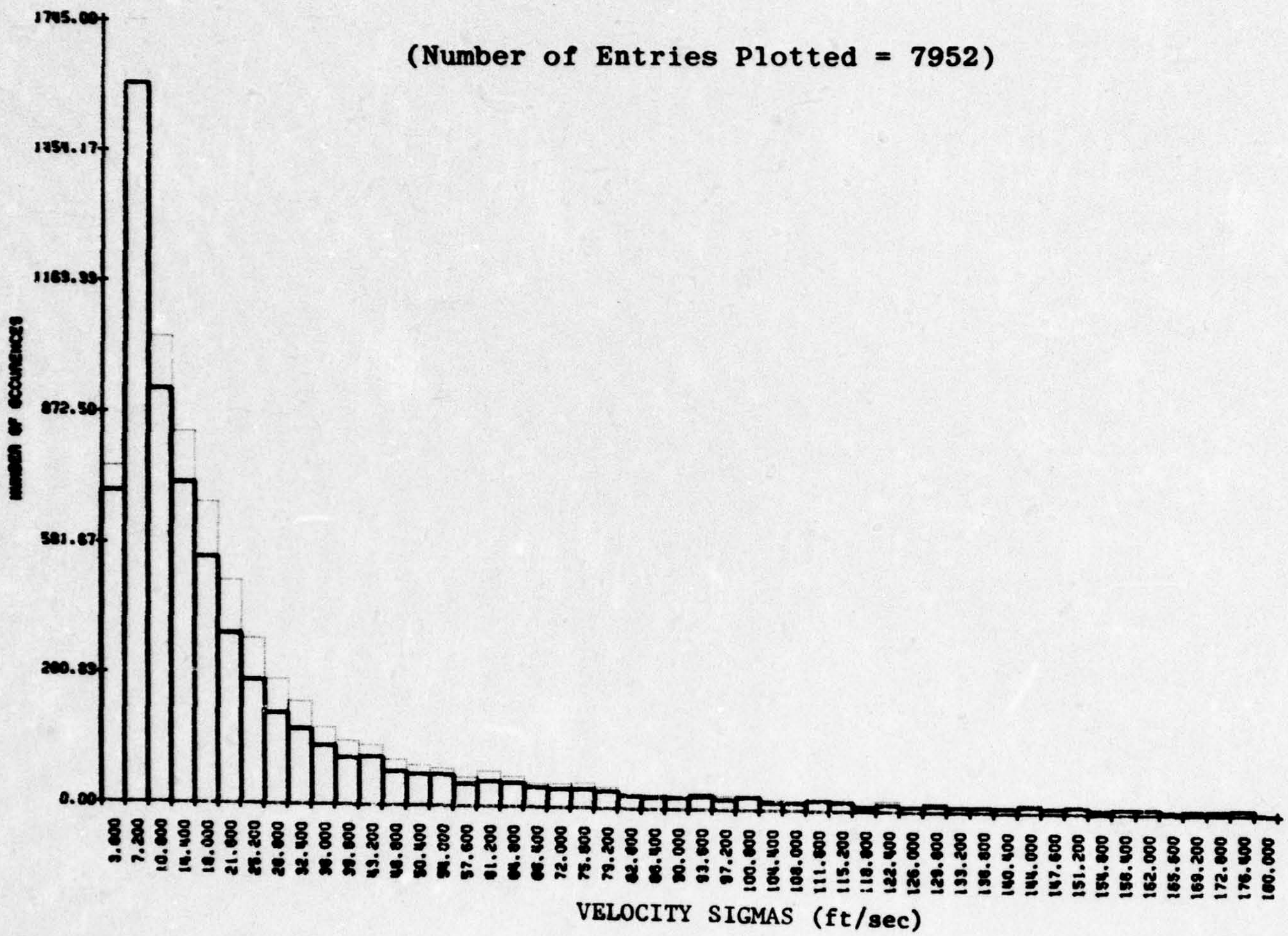

Figure 4-16a. Distribution of Velocity Sigmas for PAR Tracks
(New and Correlated PAR Tracks)

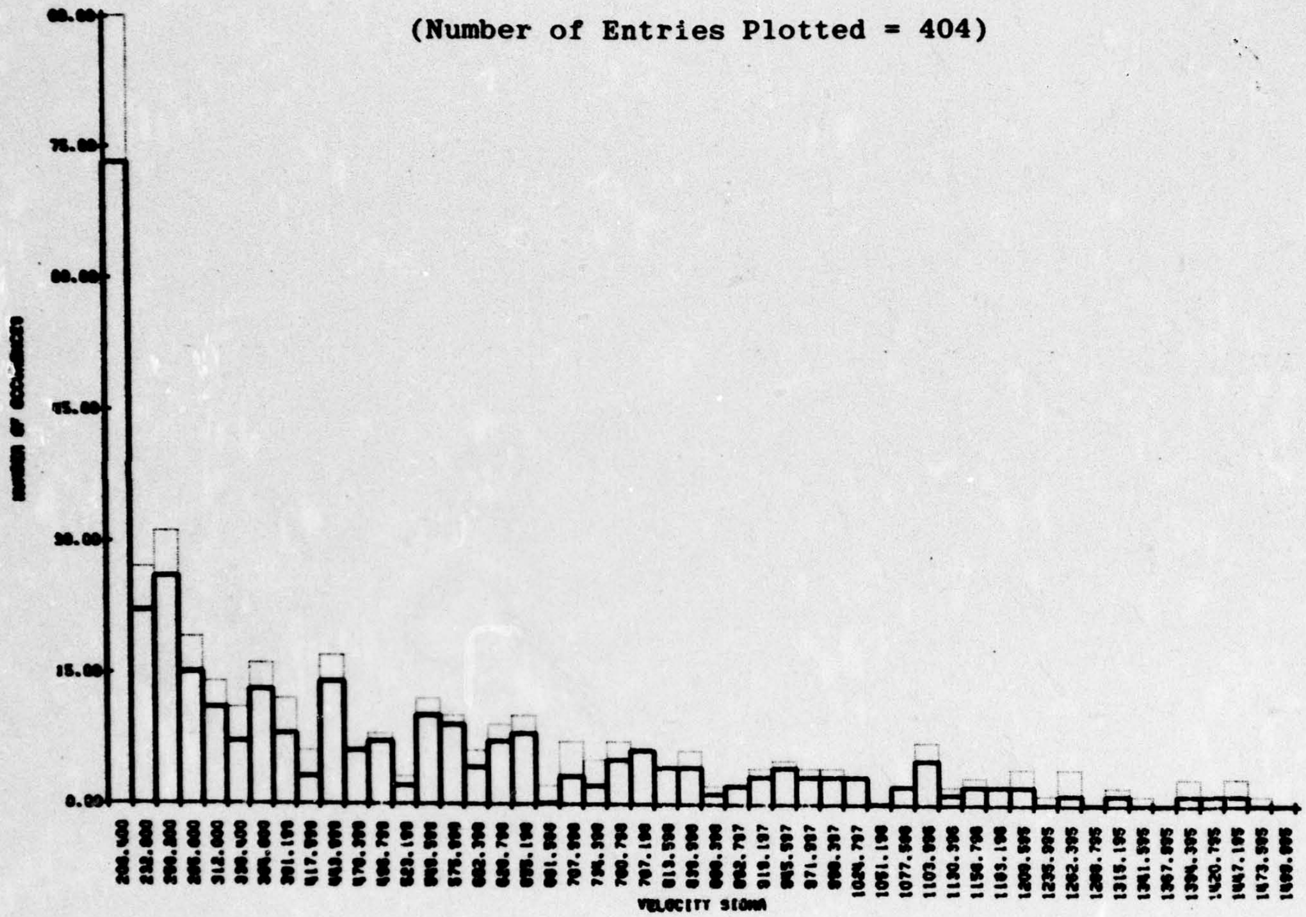

Figure 4-16b. Distribution of Velocity Sigmas for PAR Tracks
(New and Correlated PAR Tracks)
(Continuation of 4-16a with different scale)

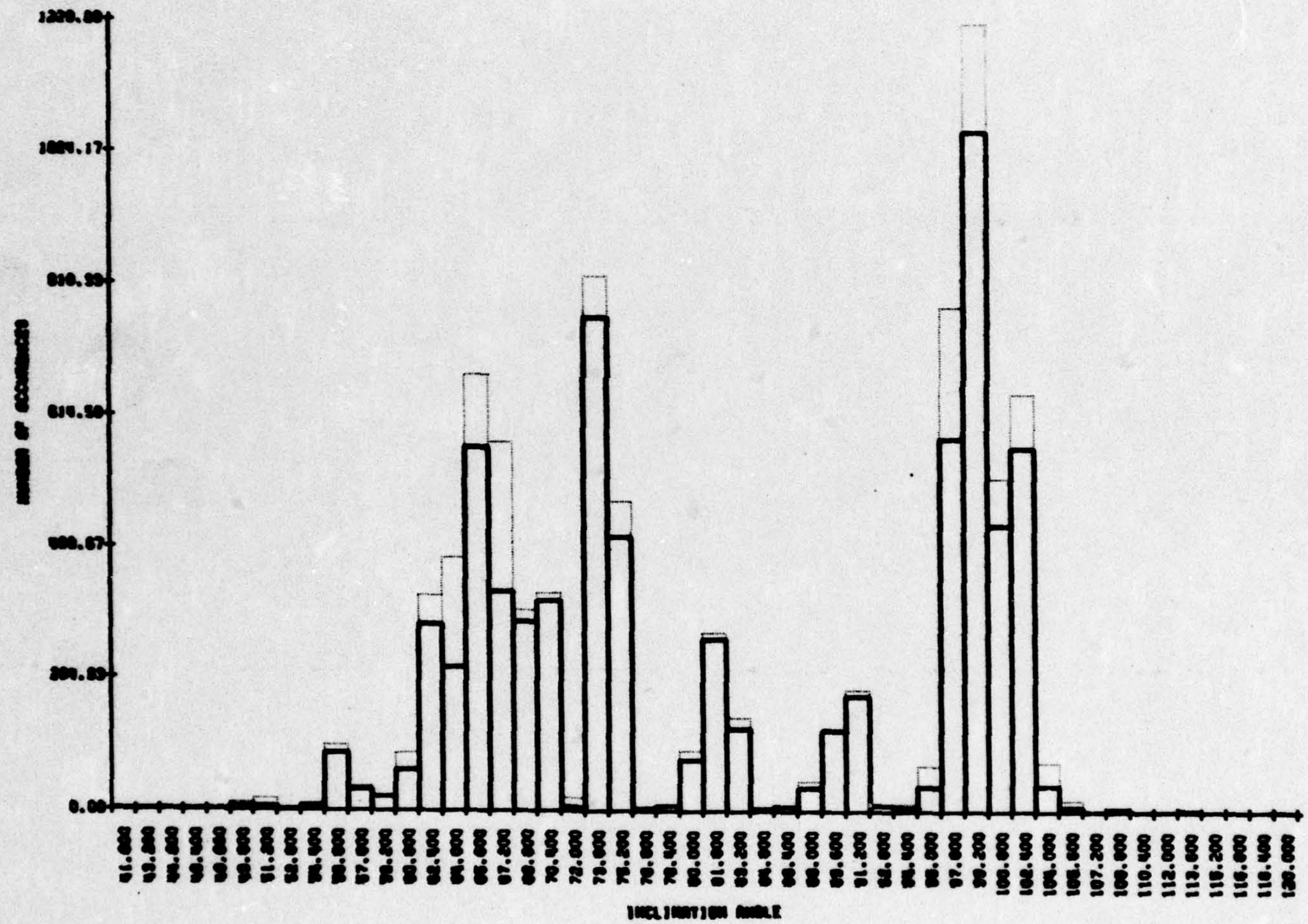

Figure 4-17. Distribution of Inclination Angles for PAR Tracks
(New and Correlated PAR Tracks)

point in the viewing volume and is not limited by the maximum elevation of the search volume.

4.2.8 Signal To Noise (S/N) Distribution

To determine the number of objects that were tracked with SN values fairly close to the usual PAR SN thresholds, the average SN for correlated and non-correlated tracks are plotted in Figure 4-18. The search detection threshold is dynamically varied as a function of false detection but varies up and down around 12 dB.

4.2.9 PAR-SDC RCS Comparisons

Figure 4-19 is a plot of the log of the SDC RCS versus the log of the PAR RCS for PAR tracks that correlate. This information is furnished since all RCS values except in the overlay to Figure 4-11a are the PAR RCS's. Using the PAR RCS's allows an accurate comparison of data from the same sensor at the same time for RCS's of the correlated and non-correlated tracks. Although the two RCS's do have the same general trend, the PAR's RCS's tend to be smaller than the SDC values. Table 4-1 compares the RCS values obtained by the average of the PAR's 2 or 3 tracks of several spheres during the experiment to the SDC catalogue values and IEEE calculated accepted values for the PAR's and the SDC's frequencies. The SDC's RCS collecting sensor is a few megacycles higher. The theoretical RCS of satellite number 2826 would not be expected to vary more than .02 m^2 over the PAR and FPS-85 frequency band.

4.2.10 Data Characteristics of Possible Breakup

Over a period of about 3 hours, there were observed 195 tracks that did not correlate with the catalogue but all had similar characteristics. The altitudes varied from 150-300 km and the inclination angles fell between 67° and 68.5°. The data for these tracks is presented in Figure 4-20 for Altitude as a function of RCS. These objects are candidates for but not necessarily all members of a breakup of a satellite. If all

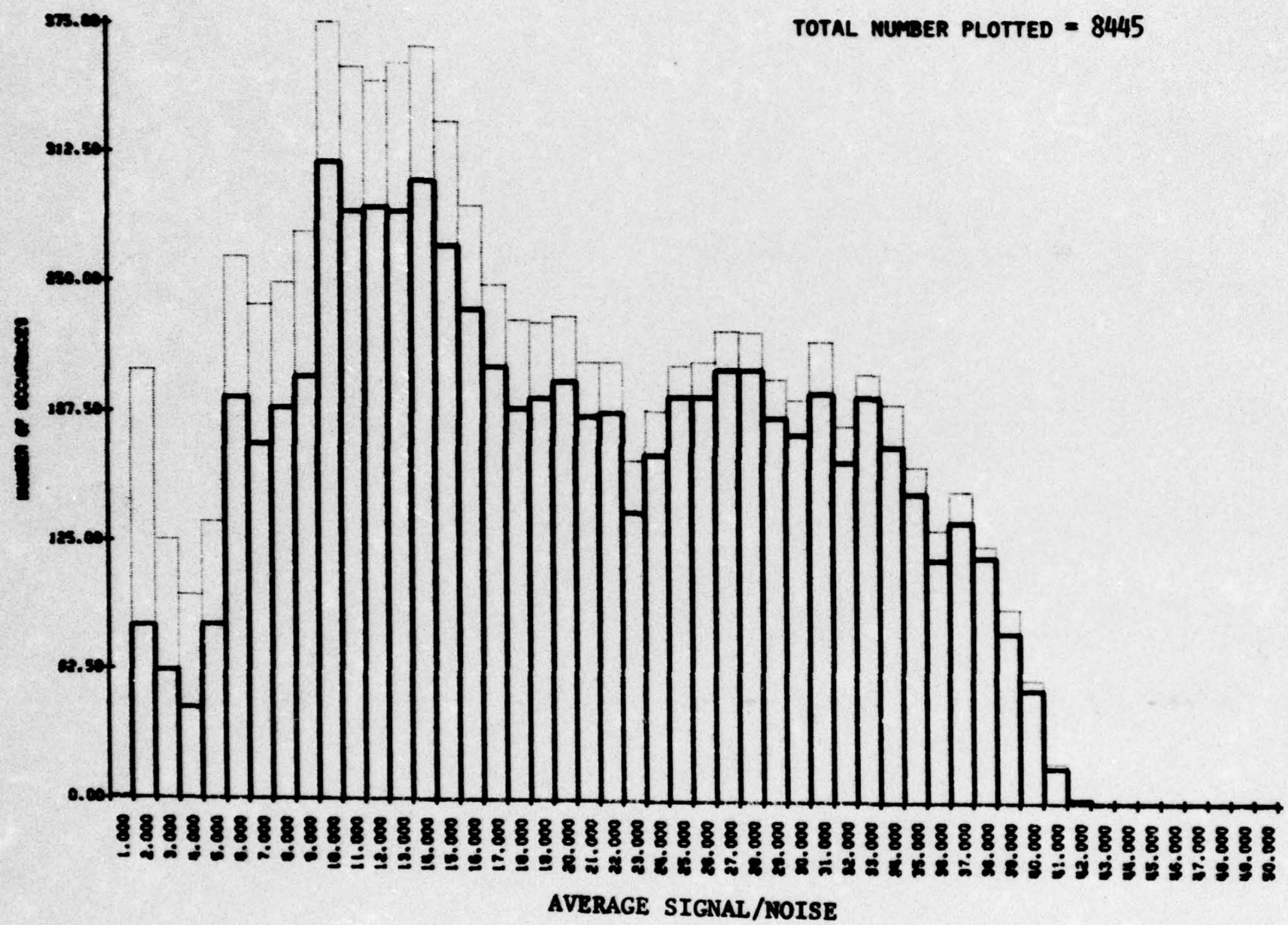

Figure 4-18. Distribution of Signal/Noise for PAR Tracks (New and Correlated PAR Tracks)

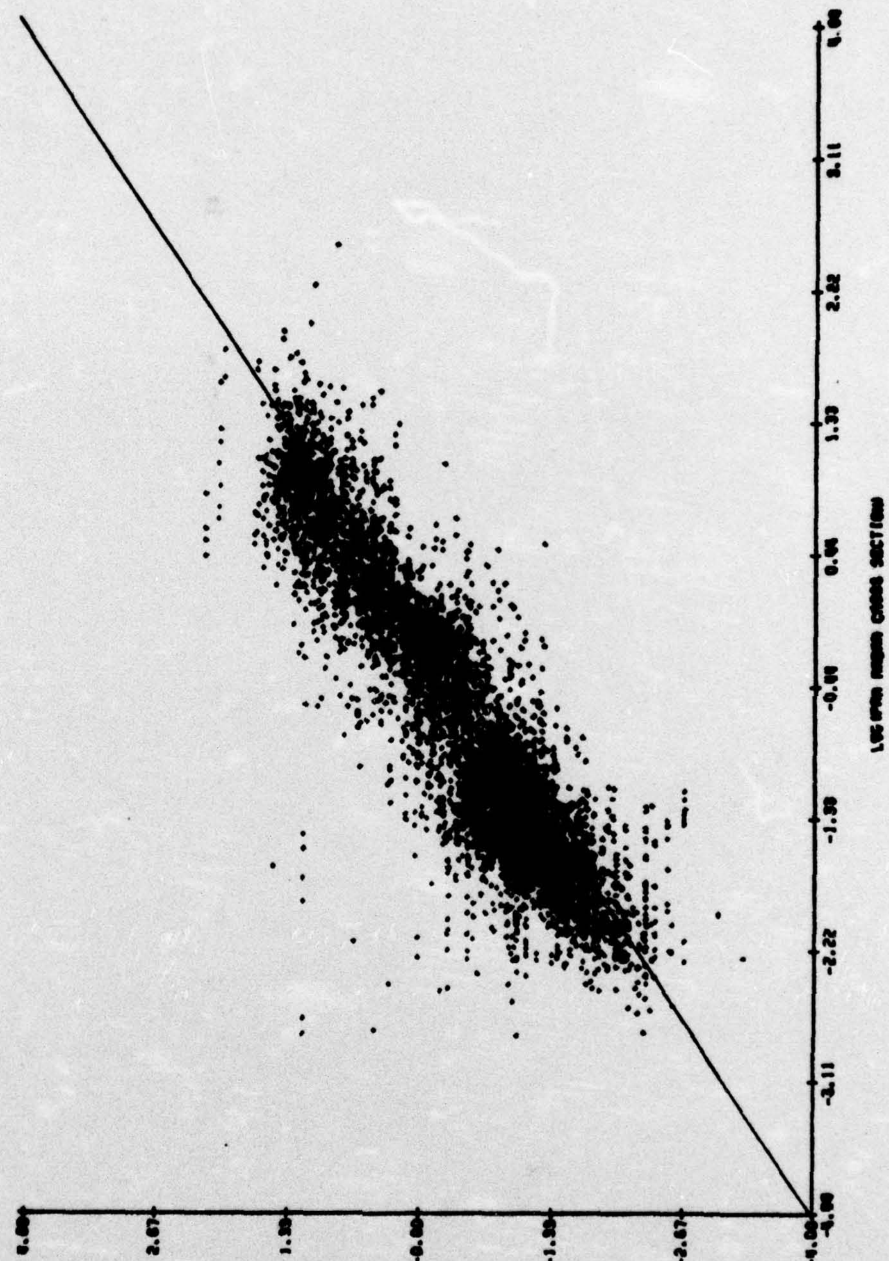

Figure 4-19. SDC and PAR RCS Comparison

TABLE 4-1. RCS COMPARISONS FOR CALIBRATED SPHERES

SAT ID	IEEE*†(PAR)	AVG. PAR*	CATALOGUE*	IEEE*†(FPS-85)
902	.049	.050	.030	.038
1520	.049	.052	.040	.038
2909	.057	.058	.115	.077
4957	.169	.177	.149	-
4963	.169	.174	.131	-
2826	.394	.422	.312	.394
5398	.911	.986	.978	.750

* SQ. METERS

† THEORETICAL VALUES

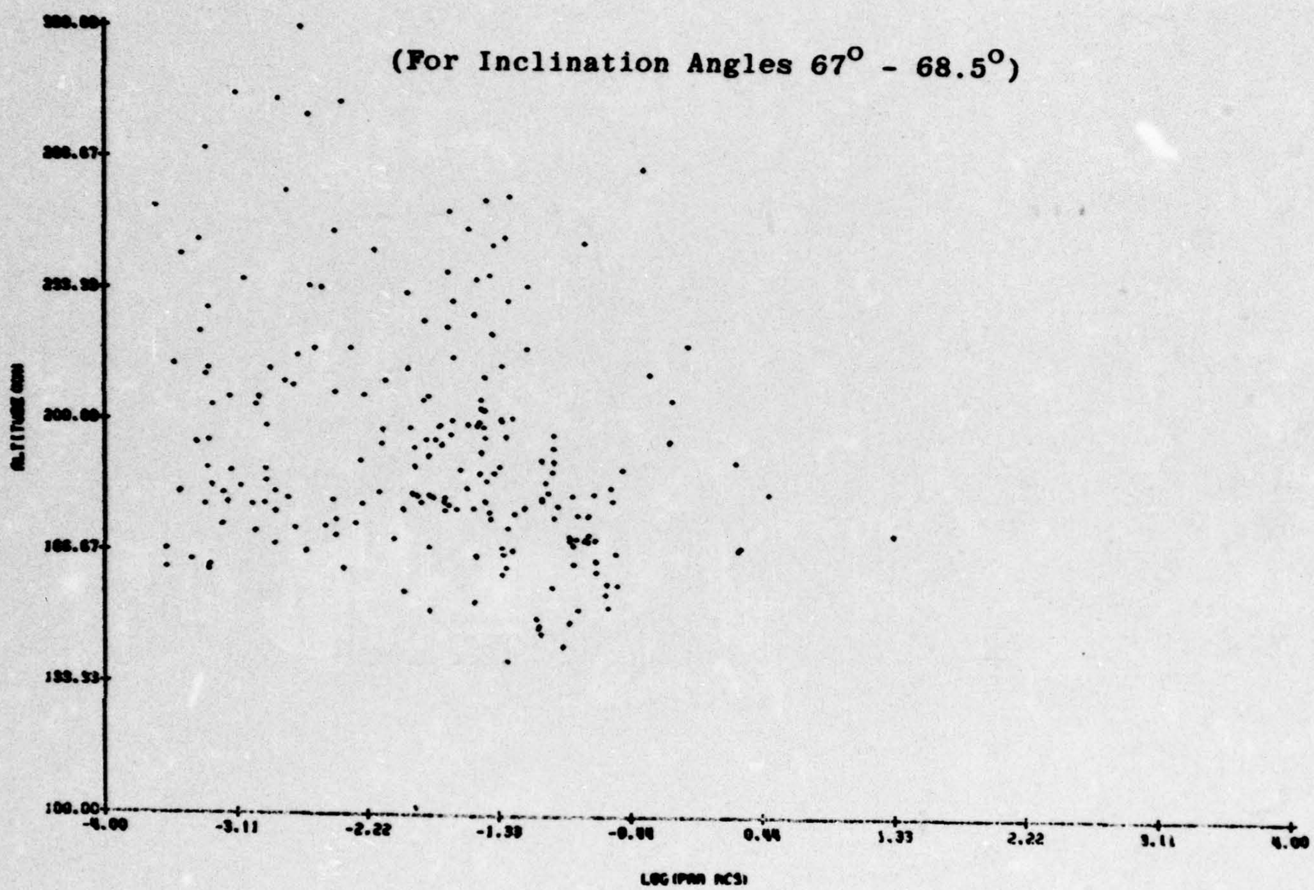

Figure 4-20. RCS Characteristics for Observed Breakup (New and Correlated Tracks)

these non-correlating tracks were ignored, the percentage of tracks not correlating would be reduced to 15.4%. It is believed that these non-catalogued objects correspond to breakup of COSMOS 844 on July 25, 1975, six days before the experiment.

4.2.11 Low Altitude Non-Correlations

Since a large percentage of the tracks below 500 km altitude did not correlate with the catalogue, some comments relative to these tracks are appropriate.

As mentioned in Section 4.2.2, the correlation distance, for tracks correlating with the catalogue, did not appear to be a function of altitude. This implies that the element sets that were in the catalogue for low altitude orbits correlated just as well as the other altitudes and that we should not expect a large number of the low altitude PAR tracks to have correlated if larger correlation bounds had been used.

There were 908 PAR tracks below 500 km altitude. This does not mean that the perigee of the orbit was any given value, just that the altitude at correlation time was below 500 km. Of these, 345 tracks correlated with the catalogue for a correlation percentage below 500 km of 38%. These 345 tracks were multiple pass tracks of 127 catalogued objects. There were 45 catalogued objects that intersected the search volume below 500 km that did not have a PAR track that correlated. Of these, 25 had element sets older than 5 days. The majority of the catalogued objects at low altitudes were tracked and did correlate with the catalogue. Therefore, the majority of the 563 tracks (62% of the low altitude tracks) that did not correlate were multiple pass tracks of objects not in the catalogue.

4.3 DATA CHARACTERISTICS SUMMARY

During the time of the data collected, there was no significant deviation of the ratio of new tracks to old tracks, thus indicating that the non-correlating tracks were time independent.

In the altitude regions applicable for this experiment, the accuracies of the PAR relative to the catalogue do not appear to be altitude or cross-section dependent.

Even considering the fact that the catalogue elements provided for this experiment were 1½ days or more old, and that the PAR can track at better than 1 km accuracy after bias corrections, it appears that the PAR can contribute to a more accurate catalogue by updating already catalogued elements. Of the tracks that did not correlate, less than 2% were within 60 nmi of an SDC vector integrated to the PAR vector time.

Considering tracks declared as new, the new objects are more predominant for smaller radar cross-section values. The low altitude PAR tracks also tend to be new objects. For example, 62% of the PAR tracks where the correlation was attempted below 500 km altitude did not correlate.

After plotting the distribution of track lengths, it appears that track length is not a contributing factor to non-correlations.

Over a period of three hours, there were observed 195 tracks that did not correlate with the catalogue but had similar characteristics. The altitudes varied from 150-300 km and the inclination angles fell between 67° and 68.5°. These objects are candidates for but not necessarily all members of a breakup of a satellite. If all these non-correlating tracks were ignored, the percentage of tracks not correlating would be reduced to 15.4%. It is believed that these objects correspond to the breakup of COSMOS 844. This data shows the capability of the PAR to recognize breakups and if the PAR were on line with a SPADATS role, real time mission planning for NASA could be further supported as well as the SDC's mission via having elements generated by the PAR instead of just observations.

Most objects catalogued at low altitude were tracked. Some low altitude elements were more than 5 days old. Thus,

the majority of low altitude PAR tracks that did not correlate with the catalogue were of objects not catalogued.

5. RECOMMENDATIONS

The data collected by the PAR is accurate in both the signature and metric quantities. Data presented in this report shows that the PAR collected low altitude and low cross-section data that is not available elsewhere.

PAR satellite data as used for this report can be utilized in three broad areas:

- o SDC Catalogue Maintenance and Upkeep
- o Spacecraft Collision Studies and Analysis
- o PAR System Studies

5.1 SDC CATALOGUE MAINTENANCE AND UPKEEP

From the data presented, it follows that the PAR could potentially contribute to the quality of the SDC catalogue. To achieve the full benefit of the PAR, the SDC should receive more PAR data than just the tasked data; i.e., in order to catalogue the 17.7% new tracks or to update out-of-date catalogue entries. To accomplish this would require the mission of SPADATS support to be given to the PAR. It is recommended that should the experiment be repeated, prior to the implementation of the full SPADATS support mission, that any uncorrelated object of cross-section greater than 10 dBsm be brought to the attention of the SDC in the most timely manner possible. Full SPADATS support can be furnished by the PAR and hence it is recommended that this role with appropriate fundings be assigned the PAR.

5.2 SPACECRAFT COLLISION STUDIES AND ANALYSIS

From a brief analysis of the collected data it appears that the data could be utilized in predicting spacecraft collision probability, i.e., using the PAR data, it is possible to compute flux densities for each cross section band. This information can be used to calculate the flux densities at various altitudes for the "unobservable" space debris via various space debris models.

Because of the extrapolative nature of these various models, the flux density at the PAR observable altitudes must be well known. It follows that since this flux must be well known, it should not rely on only one set of measurements in time.

Due to the PAR's limited sensitivity, it also follows that if the PAR's search volume was extended further upward in elevation, the PAR would detect satellites of smaller cross-section at higher altitudes than those found in this experiment.

It is thus recommended that the basic experiment be repeated approximately six times at about one month intervals and that the maximum elevation of the search volume be increased to 90^{o}.

It is also recommended that these data be processed and presented in terms of flux densities as a function of altitude, cross-section, and inclination.

5.3 PAR SYSTEM STUDIES

From the existing data various system parameters and questions can be estimated.

Specifically an analysis of: acquisition ranges vs cross section would yield valuable insight into the true detection probability of the PAR; the track covariances vs correlation distance would yield insight into the actual track accuracy vs the computed accuracy and hence predicted track accuracy; and cross section (or S/N) vs why objects were dropped or purged from track would prove valuable to PACS track.

It is recommended that efforts be devoted to further analysis of these data and data from future experiments to answer some of the open PAR/PACS system questions.

6. CONCLUSIONS

The PAR can and should support the SDC with a SPADATS mission. It has been shown here that it can potentially support both additions to the number of entries in the catalogue, support the accuracies of the entries in the catalogue, support the updating of "difficult" satellites, and reduce the number of lost and unknown satellites. The PAR could also potentially reduce the work load on the SDC by performing multi-revolution fits for unknown observations and producing element sets rather than just observations. The extent of this capability is yet to be determined.

A significant percentage of the objects tracked by the PAR did not correlate with the SDC catalogue and therefore, due to the conservative approach taken in this analysis, represented objects that probably were not in the catalogue.

Due to the number of objects not catalogued and the number that can be extrapolated to higher altitudes, there exists some higher potential for space tragedy than previously may have been expected.

7. REFERENCES

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2. "Tactical Load Module 2 (TLM2), Technical Verification (TV) Test Plan for Test 'Unknown Satellite Track' (UNKSATTRK) (PR06085, PR06086, and PR06101)", Revision 1, dated 23 July 1976, SAI-77-646-HU, by Mr. R. Roberts and Dr. J. Hendren.

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4. "Test Report, Unknown Satellite Track Test ID UNKSATTRK Run On: SAI Large Memory Dual Partition STACS Revision 1", dated 23 July 1976, SAI-77-648-HU, by Mr. R. Roberts and Dr. J. Hendren.

5. "Unknown Satellite Track Experiment, Technical Verification Test Report", dated 3 August 1976, SAI-77-675-HU, by Mr. R. Roberts and Dr. J. Hendren.

6. "Evaluation of the Potential Benefits to SPADATS of SAFEGUARD PAR Support (U)", (SECRET), by John N. Gabbard and Preston M. Landry, 1 July 1975, Directorate of Analysis, Asst. DCS/Pgms and Rqmts, Headquarters NORAD/ADC.

7. "Additional Analysis of PAR Satellite Tracks 1975 (U)", (SECRET), by Dr. J. Hendren and Mr. F. Bolden, February 1976, SAI-76-257-HU.